Arctic Low Cloud-Sea Ice-Stability Interactions and the Arctic Surface Energy Budget

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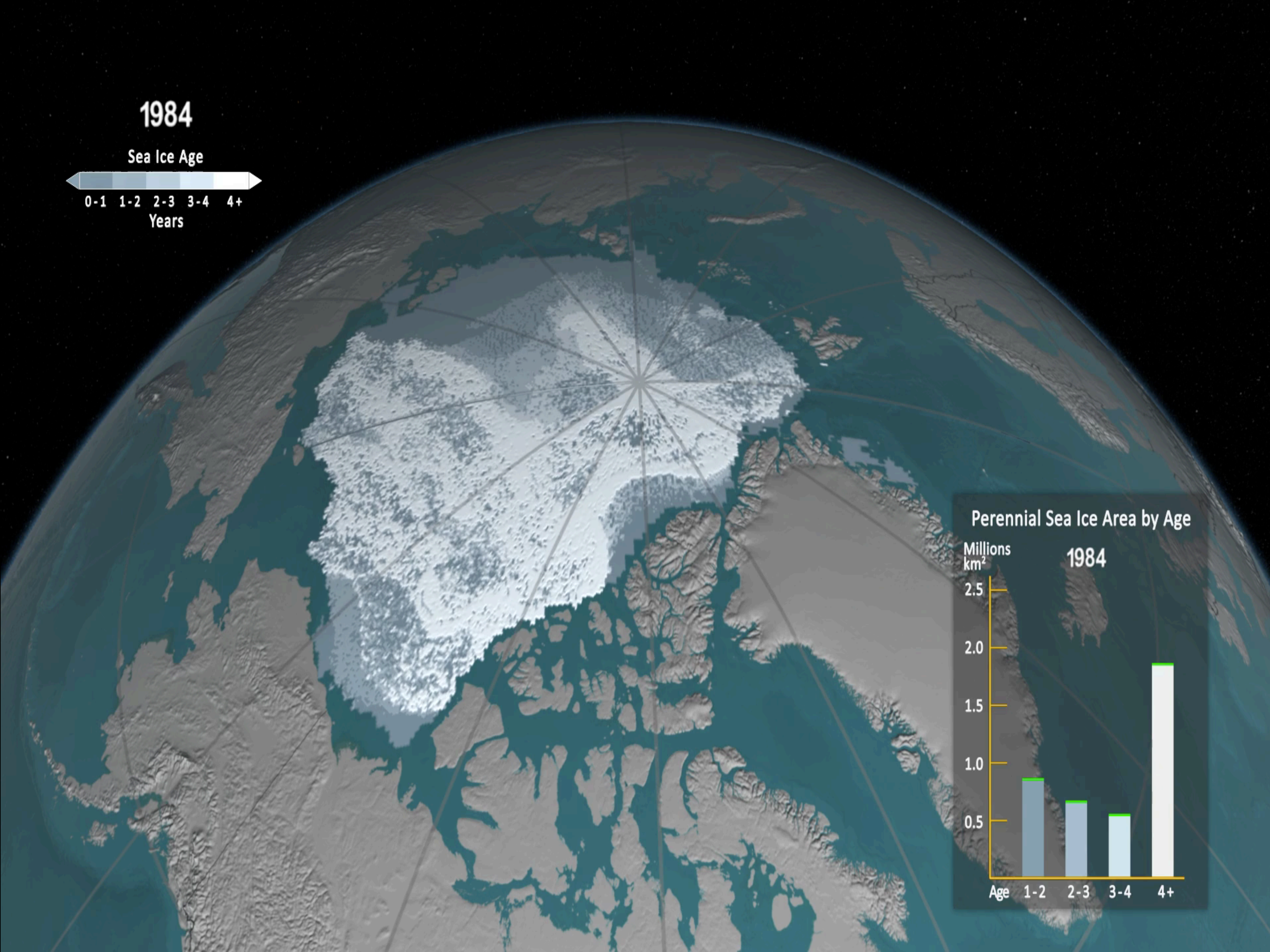
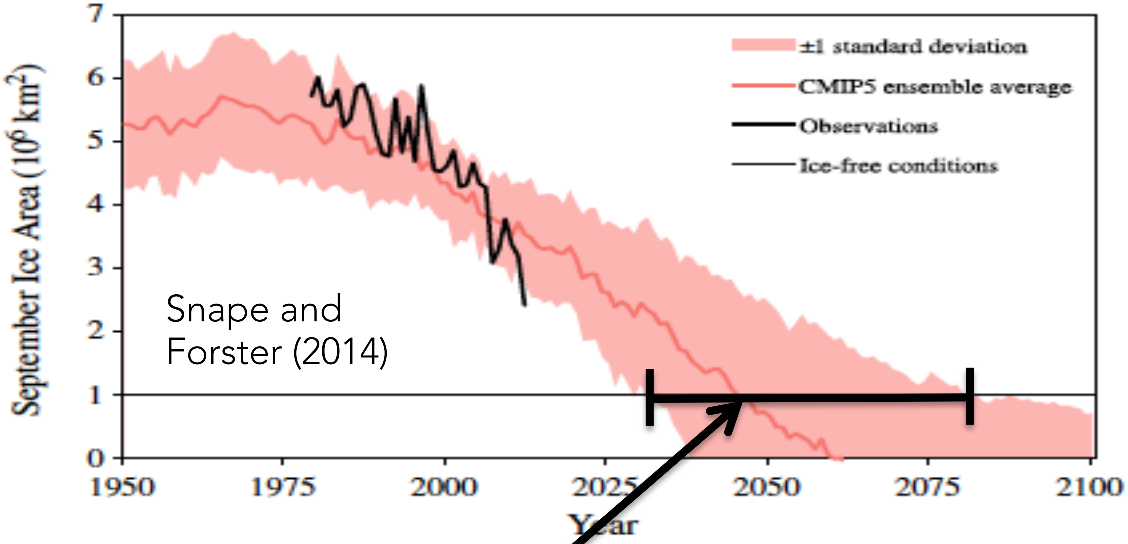
Acknowledgements: R. Boeke, B. Hegyi, S. Kato, K.-M. Xu and M. Cai


1984
Sea Ice Age
0-1 1-2 2-3 3-4 4+
Years
Perennial Sea Ice Area by Age
Millions km²
1984
2.5
2.0
1.5
1.0
0.5
Age 1-2 2-3 3-4 4+

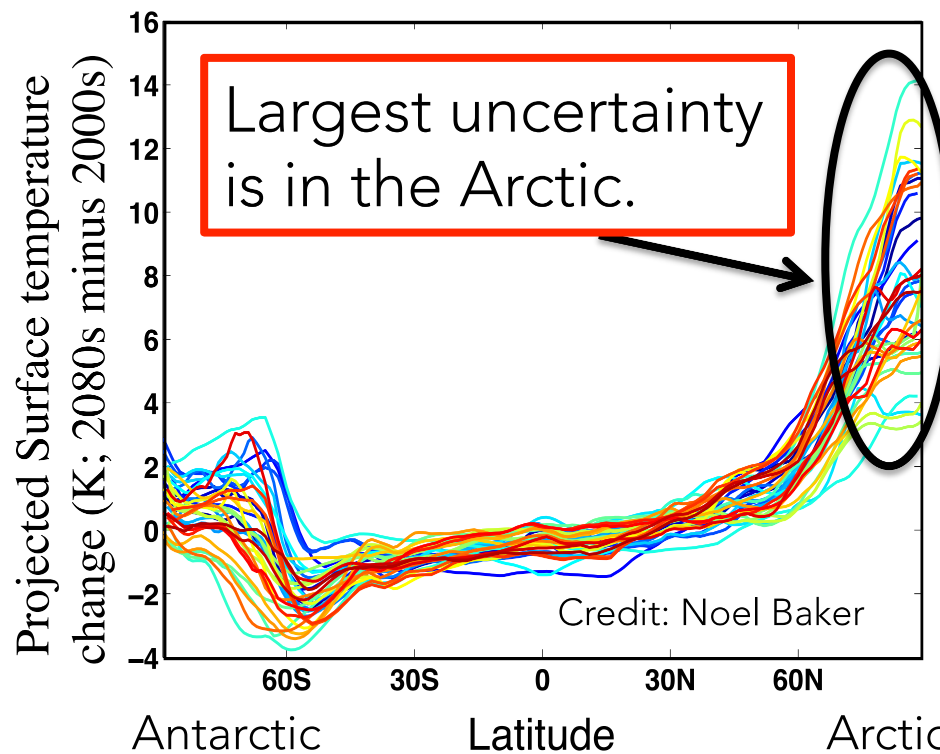
Oh, the uncertainty…



~50-year range in the projected first appearance of and ice-free Arctic

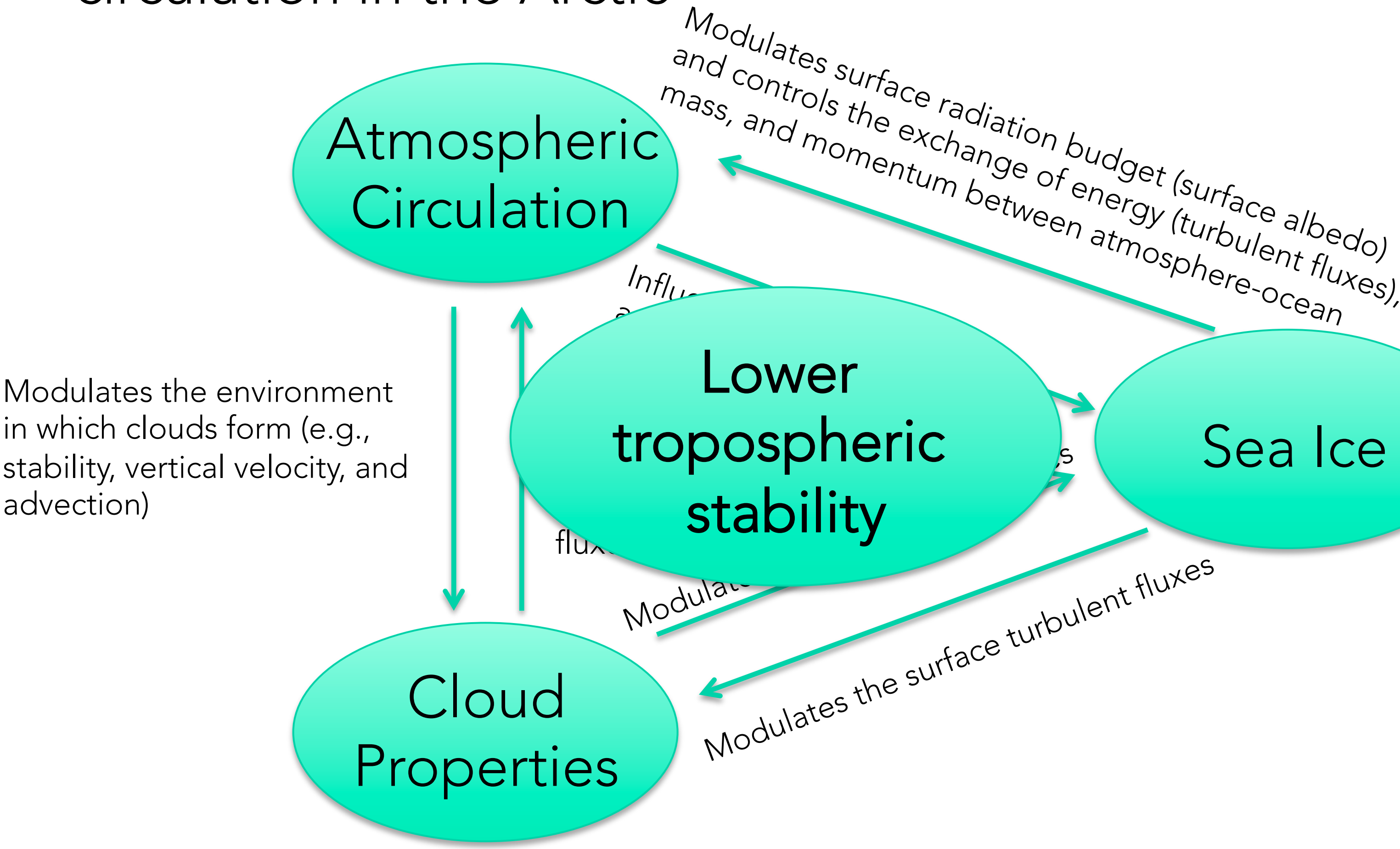
Projections of future Arctic sea ice decline and the timing of the first occurrence of a sea ice-free Arctic are very uncertain.

The large spread in climate model predictions of Arctic warming is attributed to model of sea ice melt and how it feeds back on the other components of the climate.



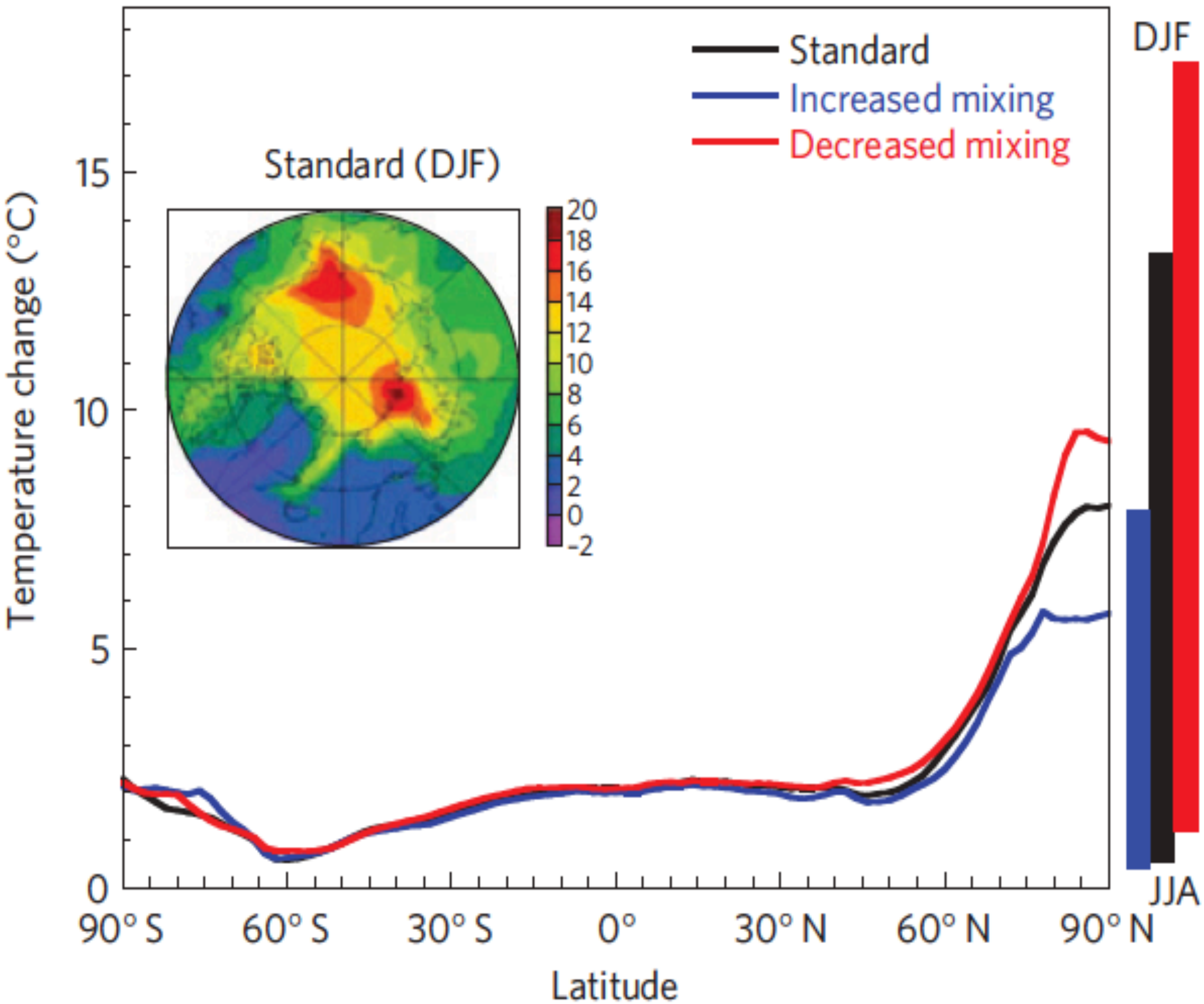
Another 3-legged stool?

Understanding the coupling between the cloud and circulation in the Arctic



In the Arctic, we cannot consider the interactions between clouds and the circulation without considering the sea ice state because sea ice influences both clouds and circulation.

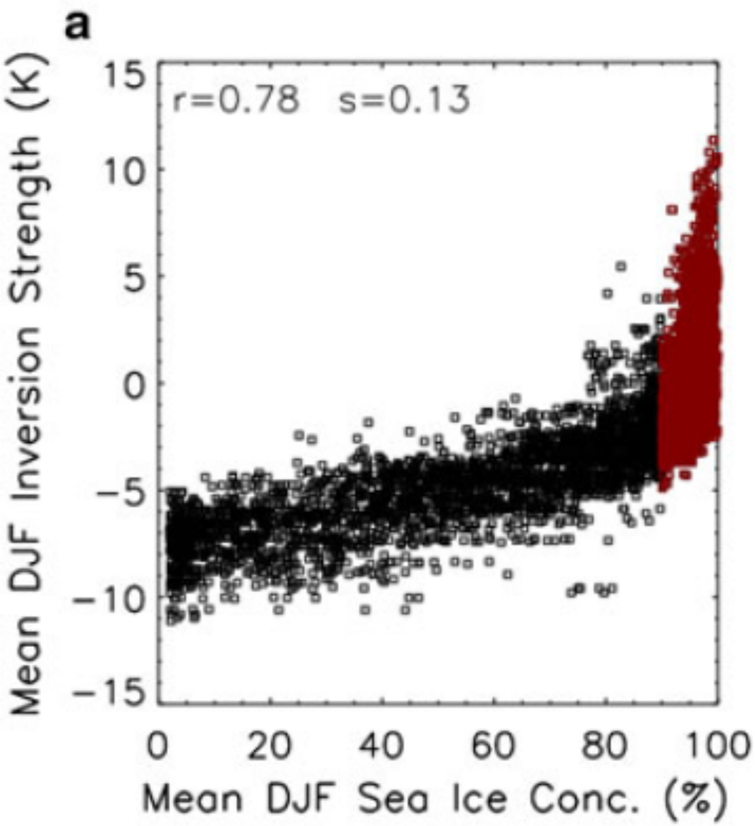
The impact of Lower Tropospheric Stability on Arctic Climate Change

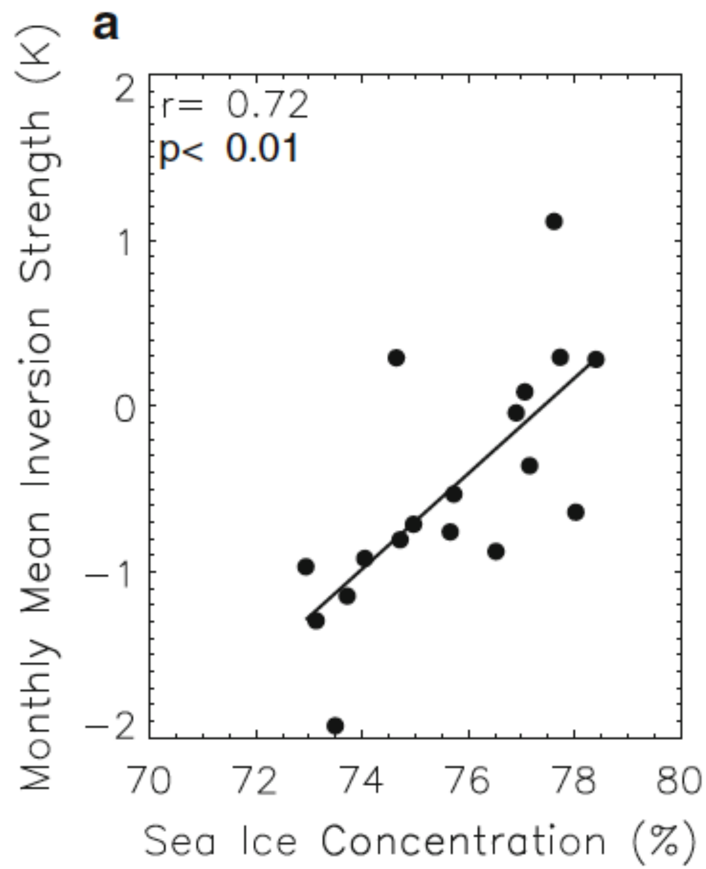


Stronger lower tropospheric stability and weaker turbulent mixing yields stronger Arctic warming.

Bintanja et al. 2011

Relationship between Lower Tropospheric Stability and Arctic sea ice cover





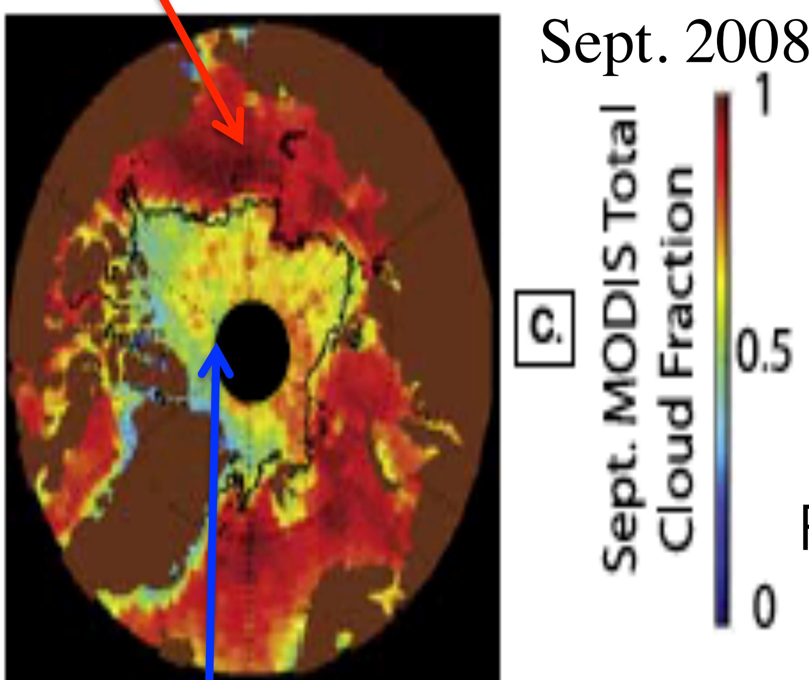
Lower tropospheric stability is strongly correlated in space and time the monthly average sea ice concentration (Pavelsky et al. 2011).

Sea ice-Cloud Interaction: Some Observational Evidence

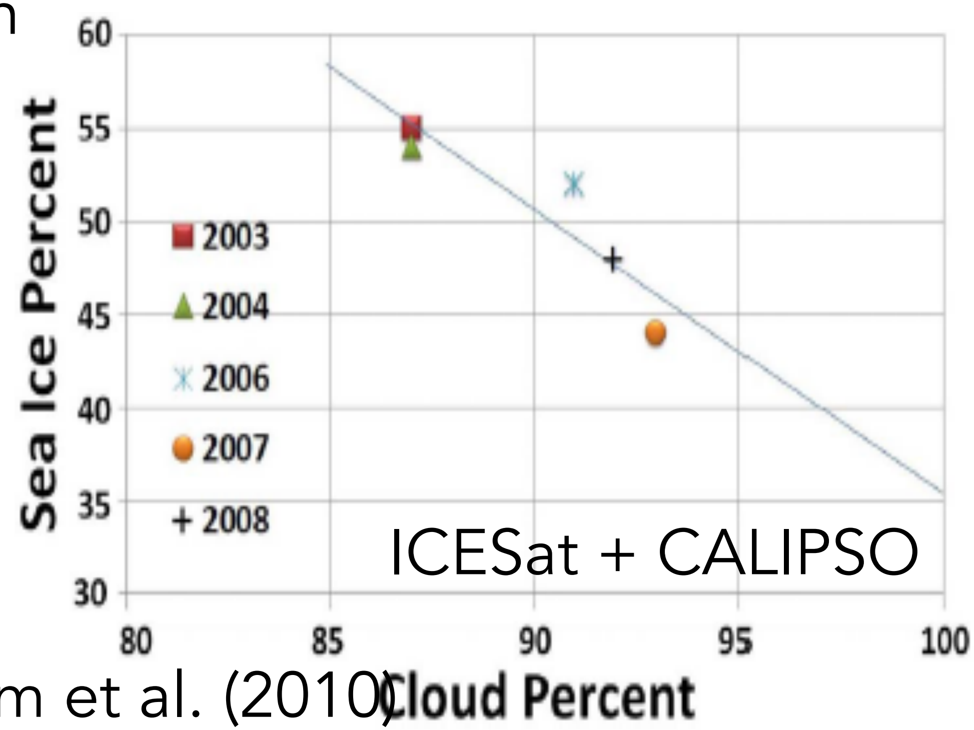
Significant correlation between cloud fraction and the sea ice extent in AUTUMN: larger cloud fraction over open water and lower cloud fraction over ice.

Larger cloud fraction over ocean

Kay and Gettelman (2009)



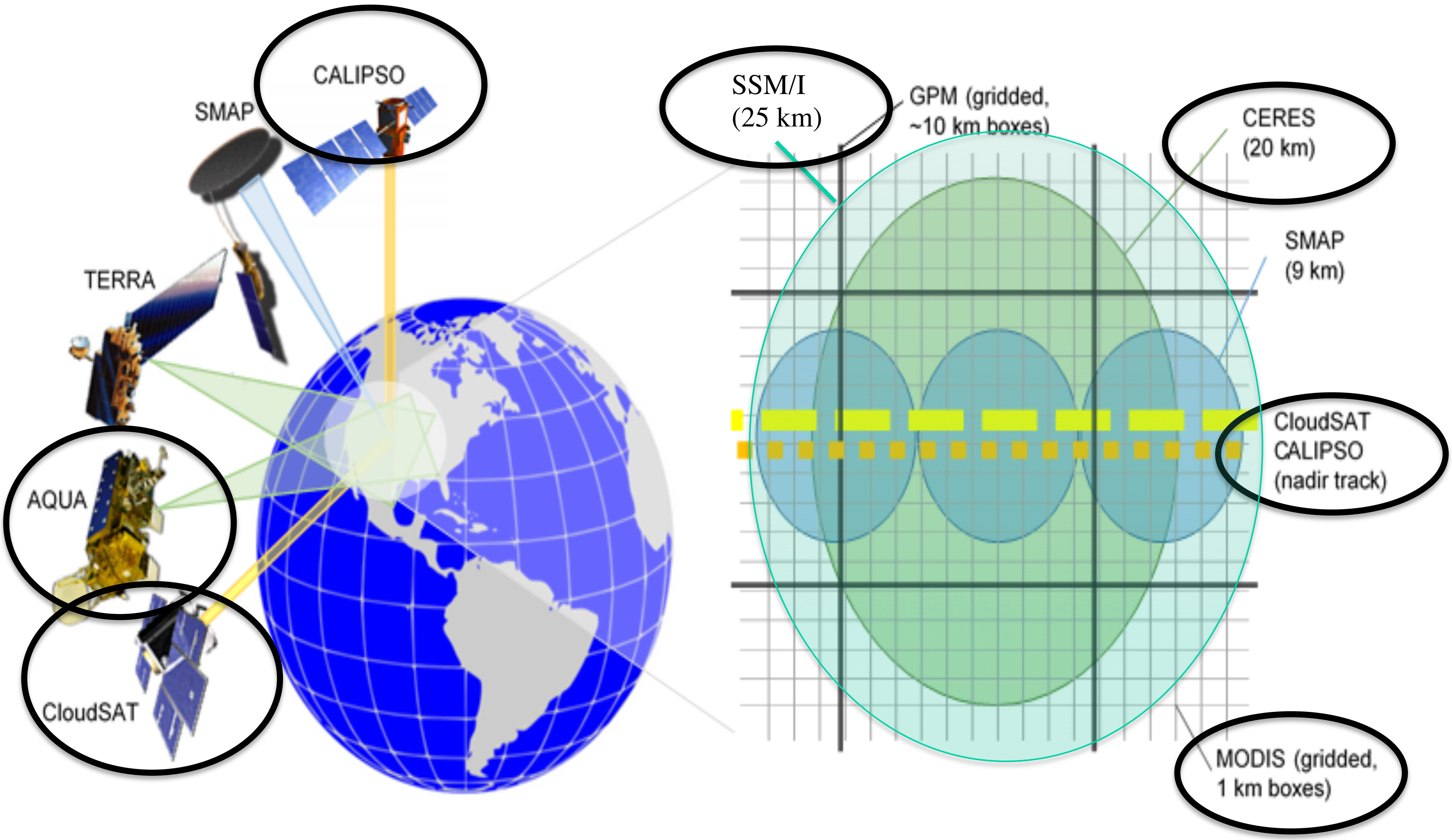
Smaller cloud fraction over sea ice



Palm et al. (2010)

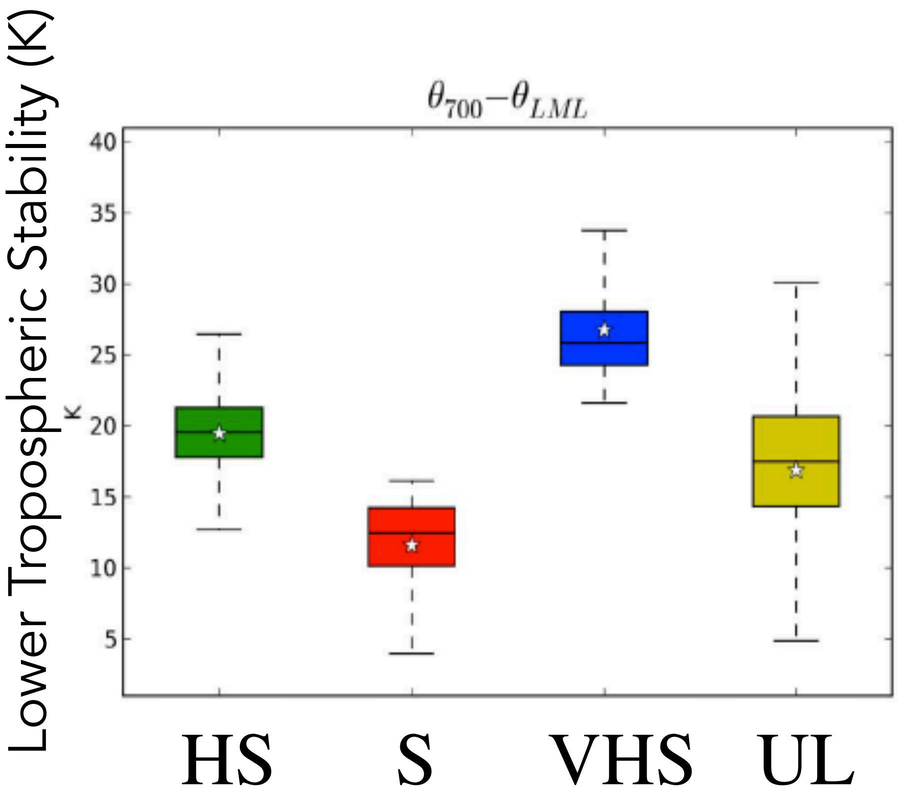
No relationship during summer because the atmosphere and surface tend to be decoupled.

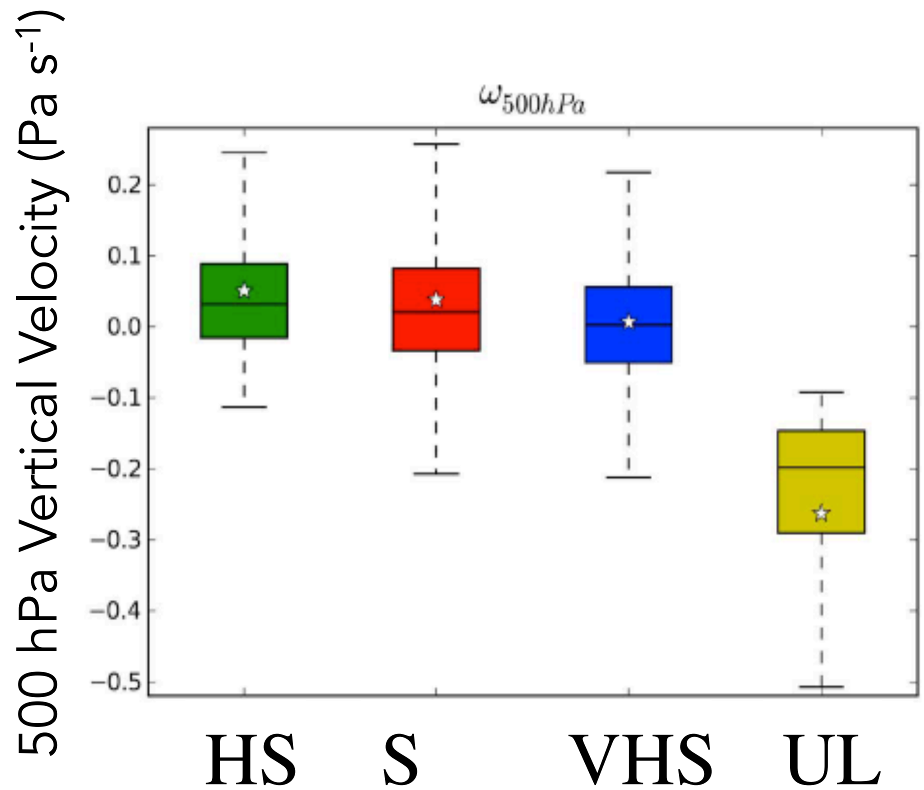
That's the power of…Data Fusion!?



A new perspective is enabled by leveraging advances in data fusion made at NASA Langley Research Center—combining CALIPSO, CloudSAT, CERES, and MODIS.

Atmospheric Regimes
(Barton et al. 2012)

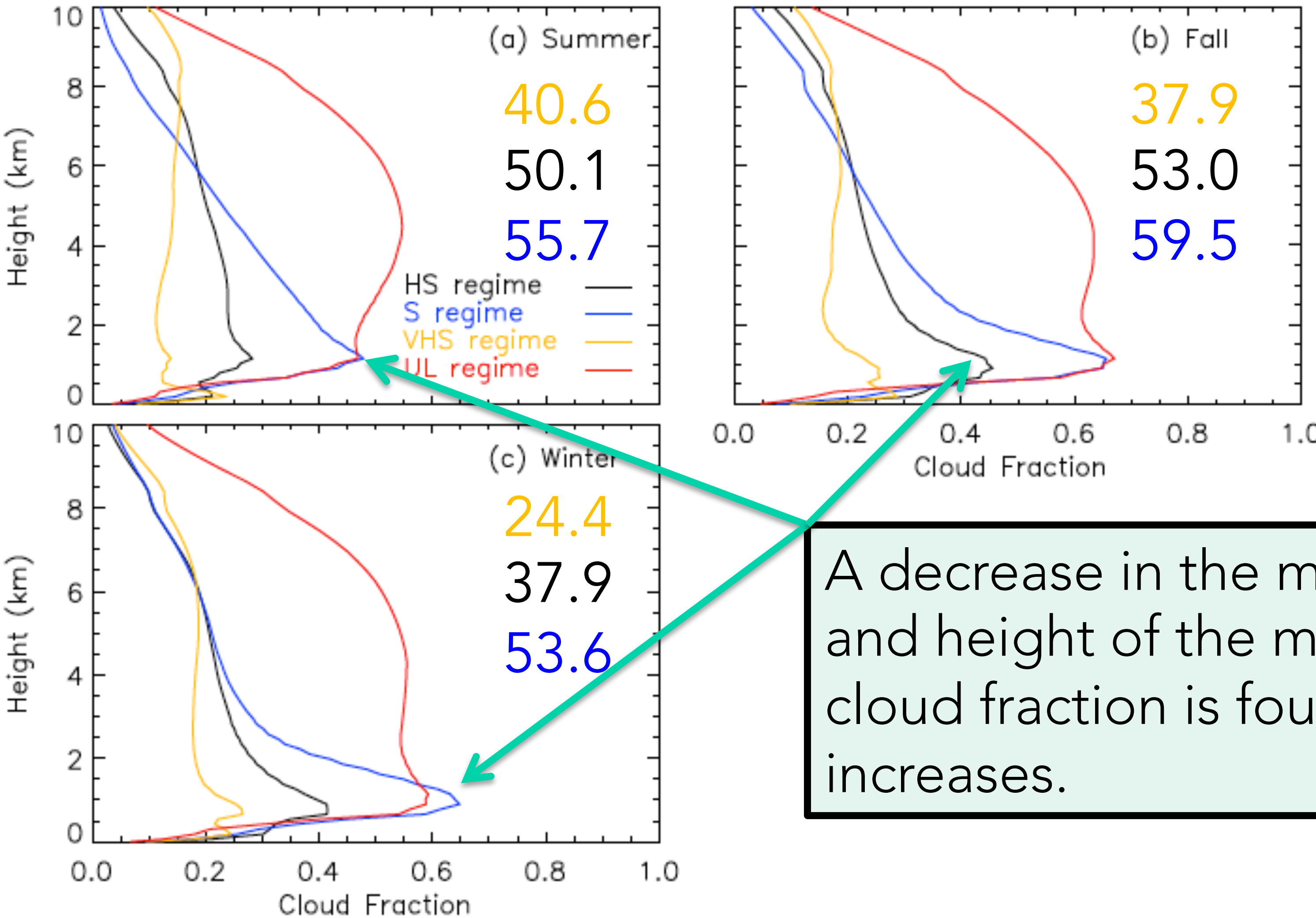




Atmospheric state regimes determined using K-means cluster analysis.

High Stability (HS): 16 K < LTS < 24 K
Stable (S): LTS < 16 K
Very High Stability (VHS): LTS > 24 K
Uplift (UL): ω_{500} < -0.1 Pa s^{-1}

How does meteorology influence Arctic clouds?

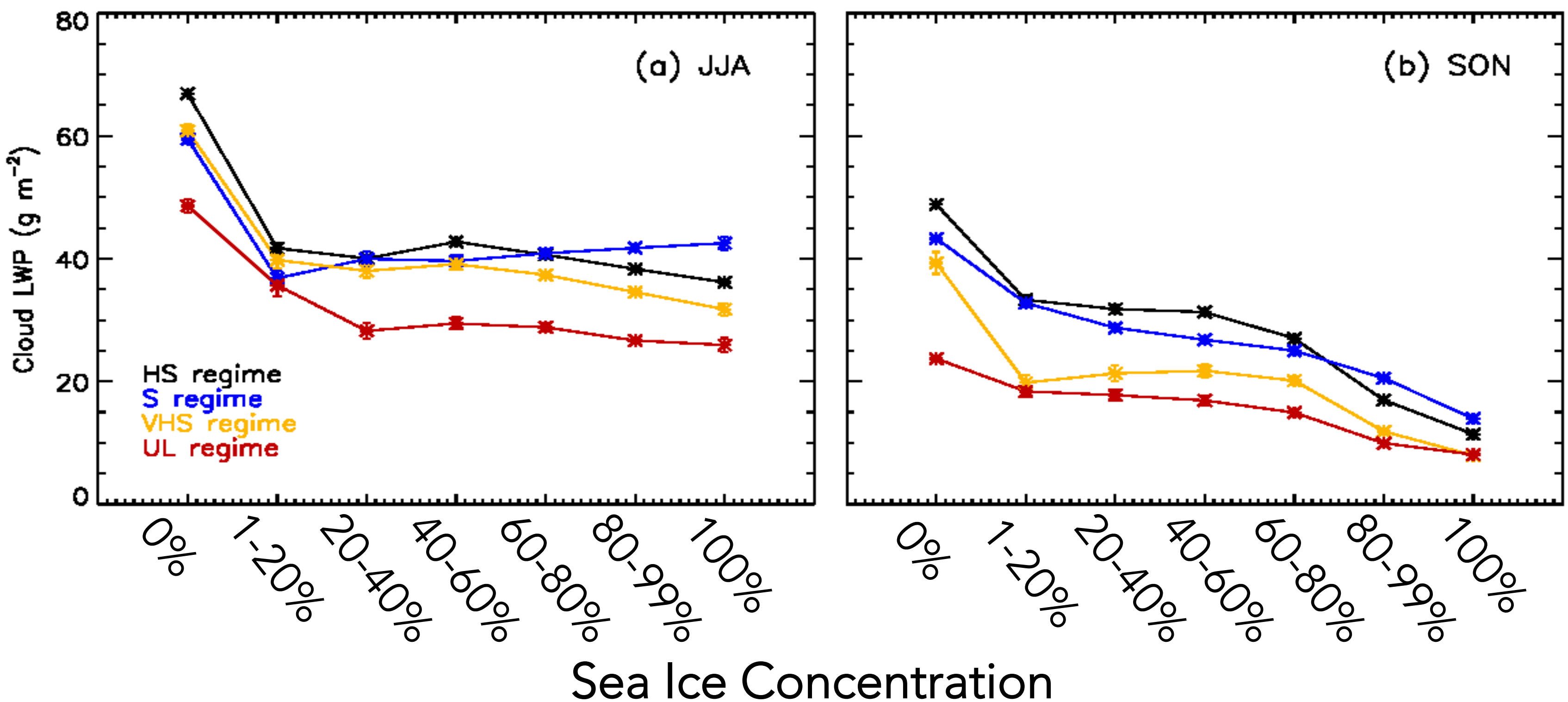


A decrease in the magnitude and height of the maximum cloud fraction is found as LTS increases.

Takeaway Message: Meteorology places a strong constraint on cloud behavior.

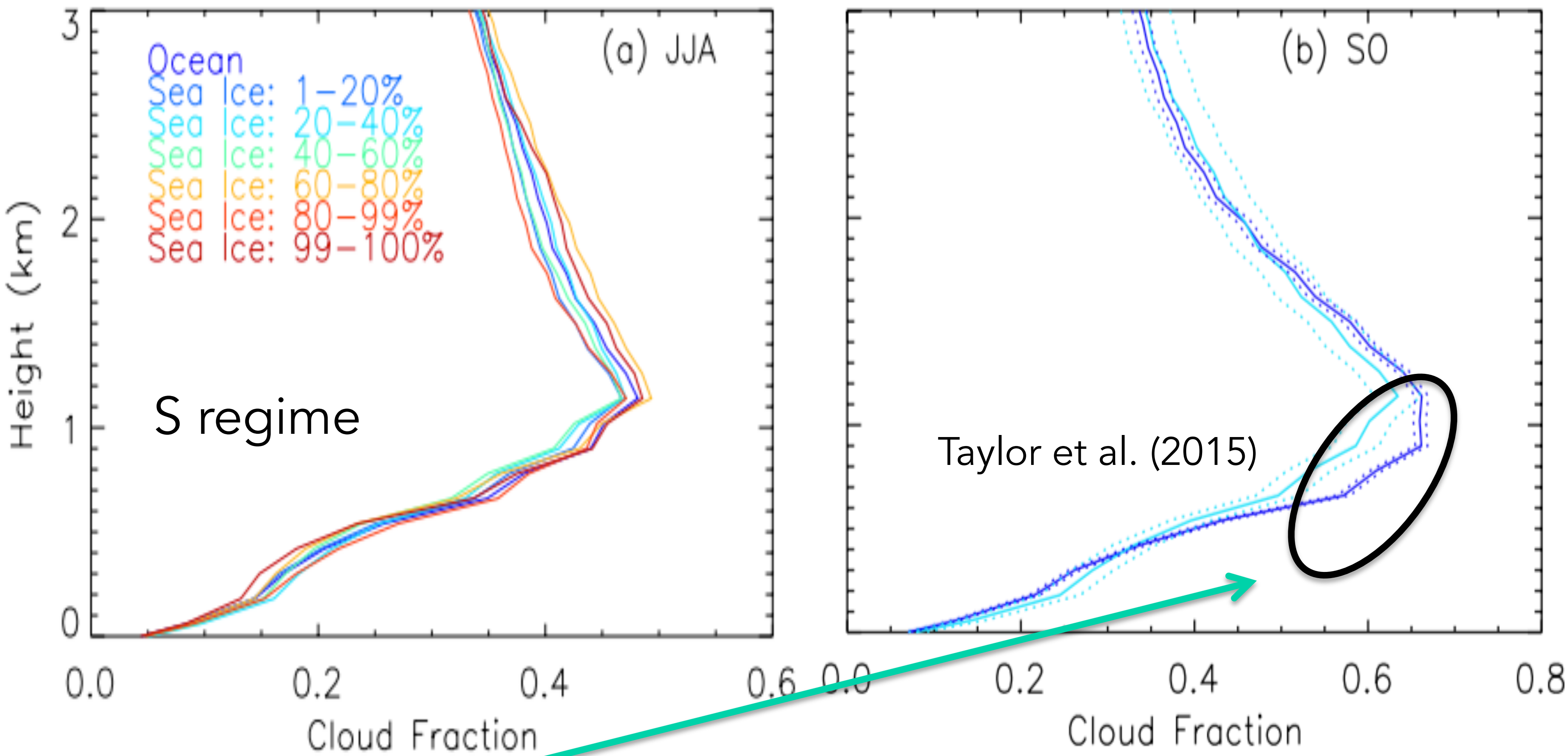
Compositing Methodology

(1) Determine the Atmospheric Regime of each footprint using MERRA
(2) Determine the instantaneous sea ice concentration from SSM/I retrieval
(3) Average low cloud properties (cloud top < 3 km) within each atmosphere and sea ice concentration bin



The goal of the methodology is to retain as much process level information as possible by using satellite footprint level data, not monthly mean gridded.

CF Vertical Profile vs. Sea ice

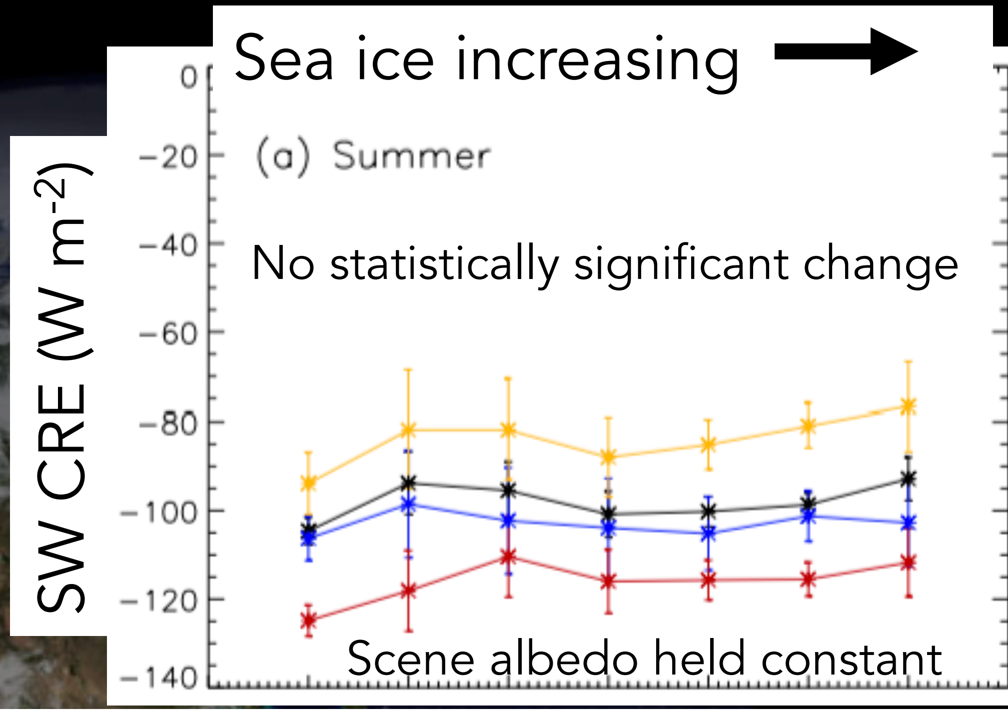


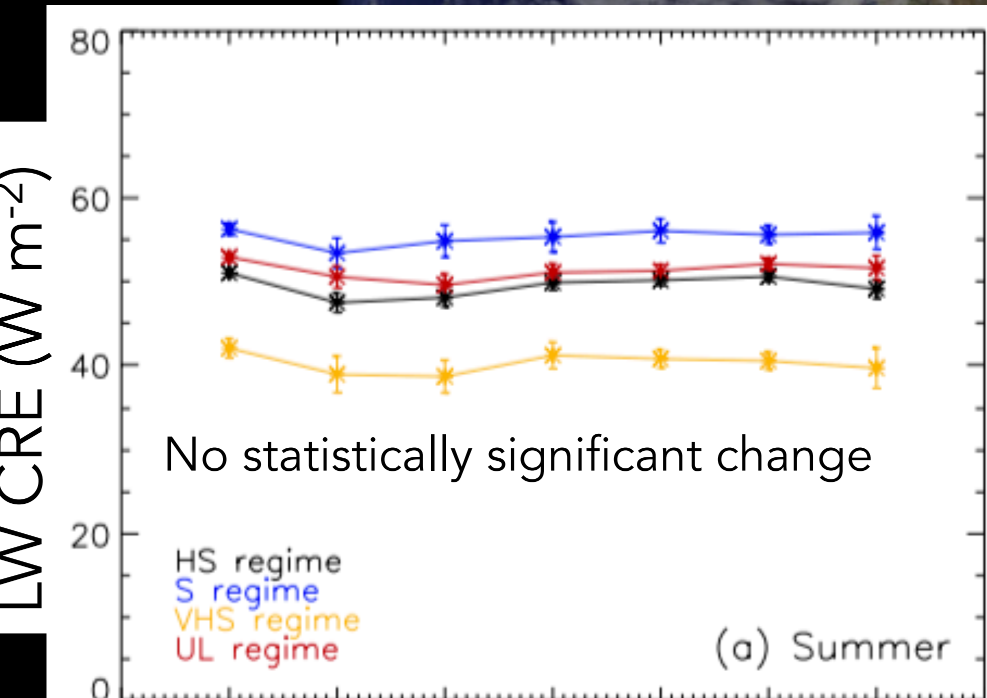
- General decrease in cloud fraction is found with increased sea ice concentration in in autumn, but no response in summer.
- Statistically significant differences at the 95% confidence interval are found at between 500 m and 1.2 km in autumn at 0% and 20-40% sea ice concentration.

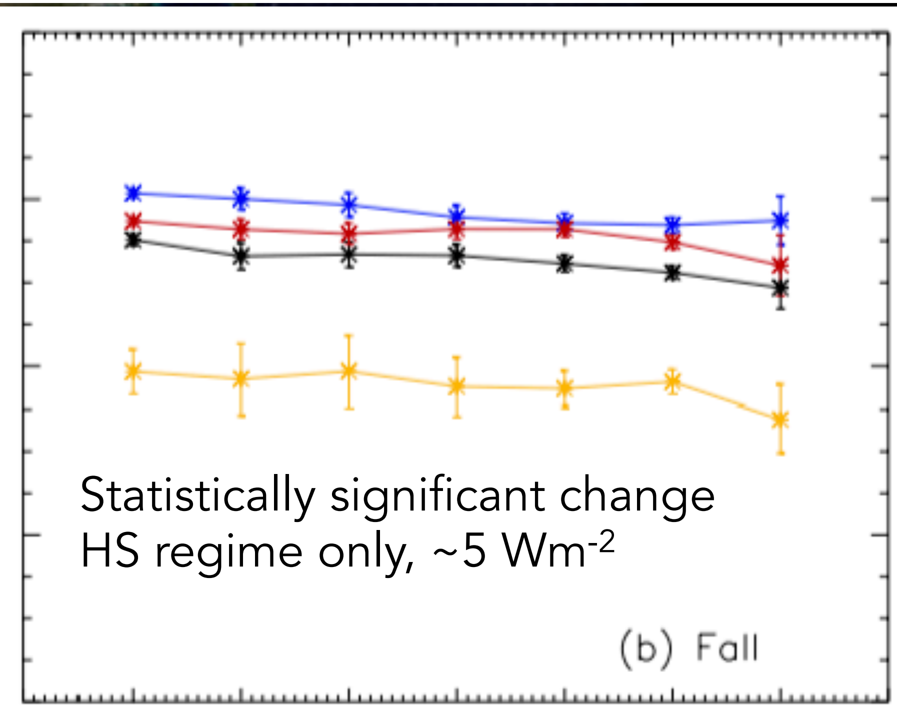
CRE vs. SIC:

Large differences in LW and SW CRE in scene with different sea ice concentrations are found but few are statistically significant.

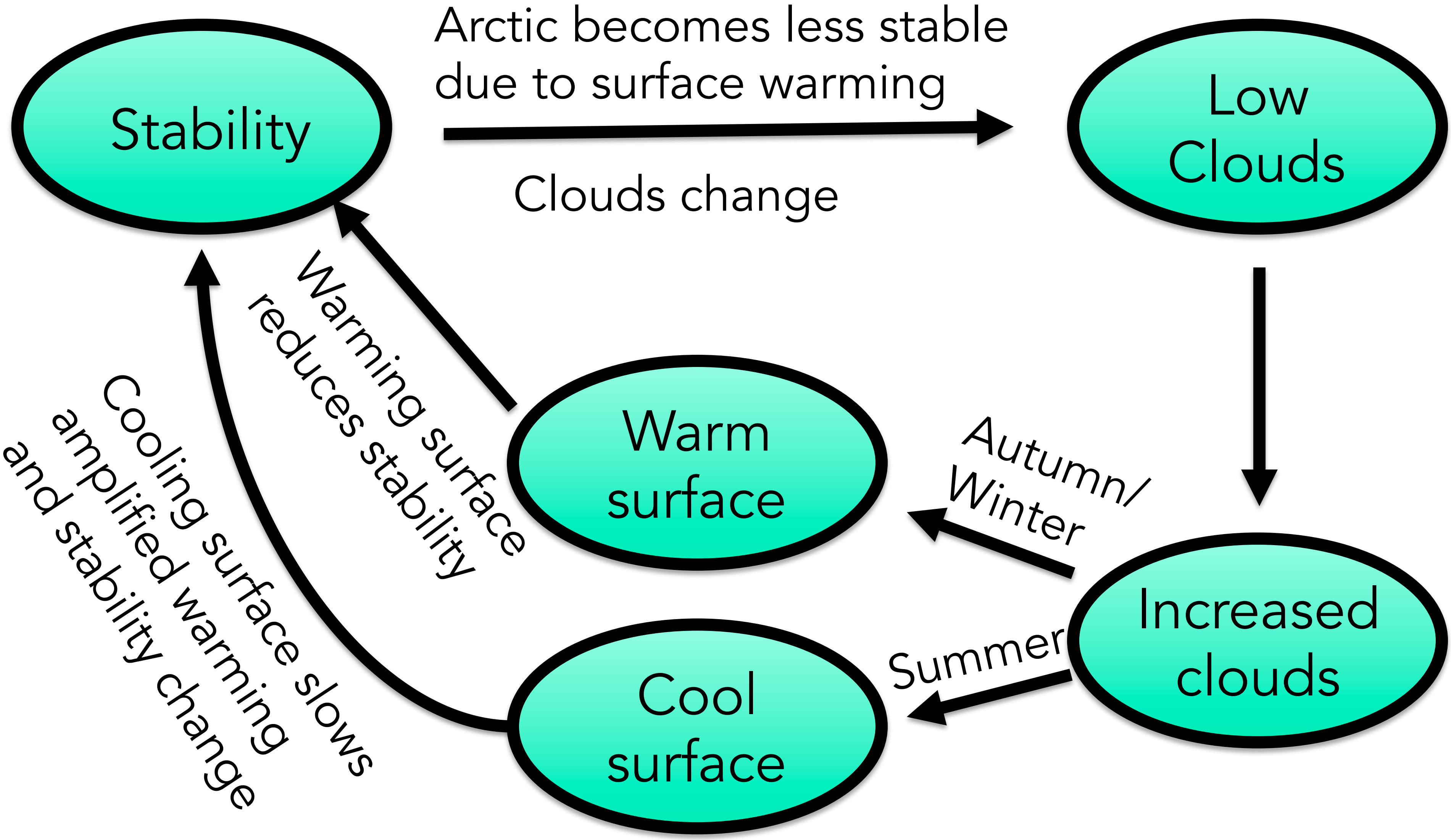
Taylor (2017)





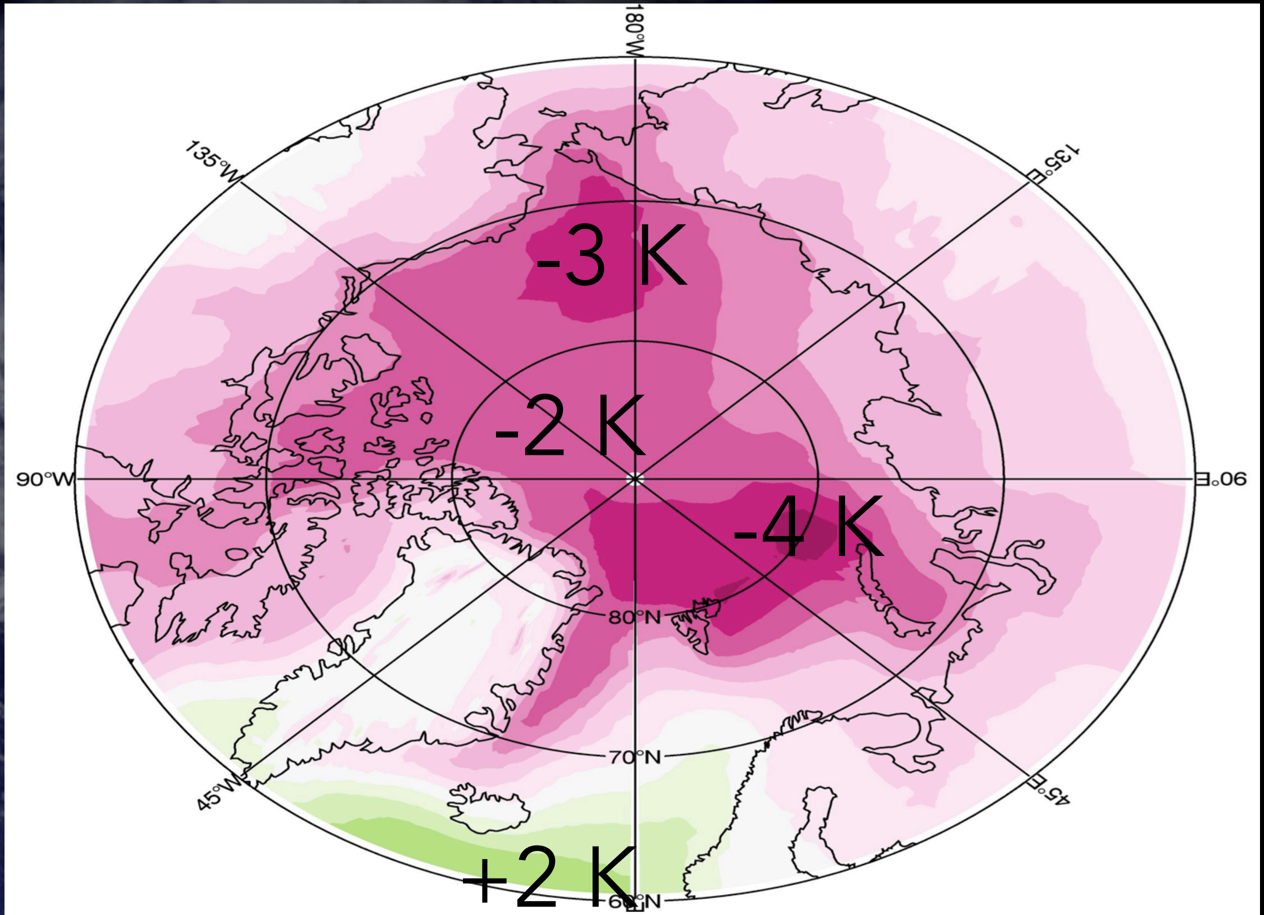


Stability-Cloud Response Pathway



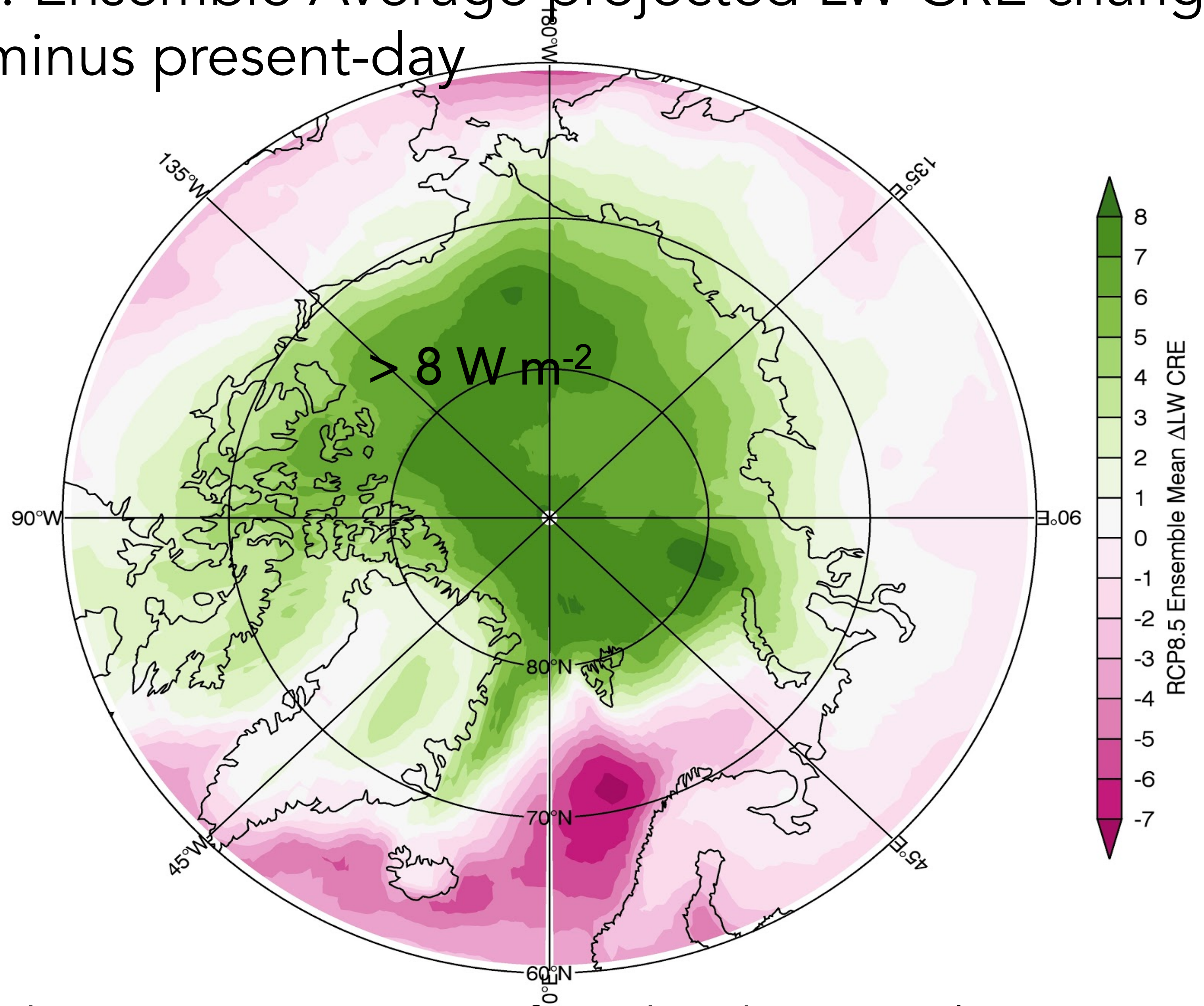
Future changes in Arctic LTS: RCP 8.5

Overwhelmingly, CMIP5 models project significant decreases in LTS over the central Arctic Ocean.



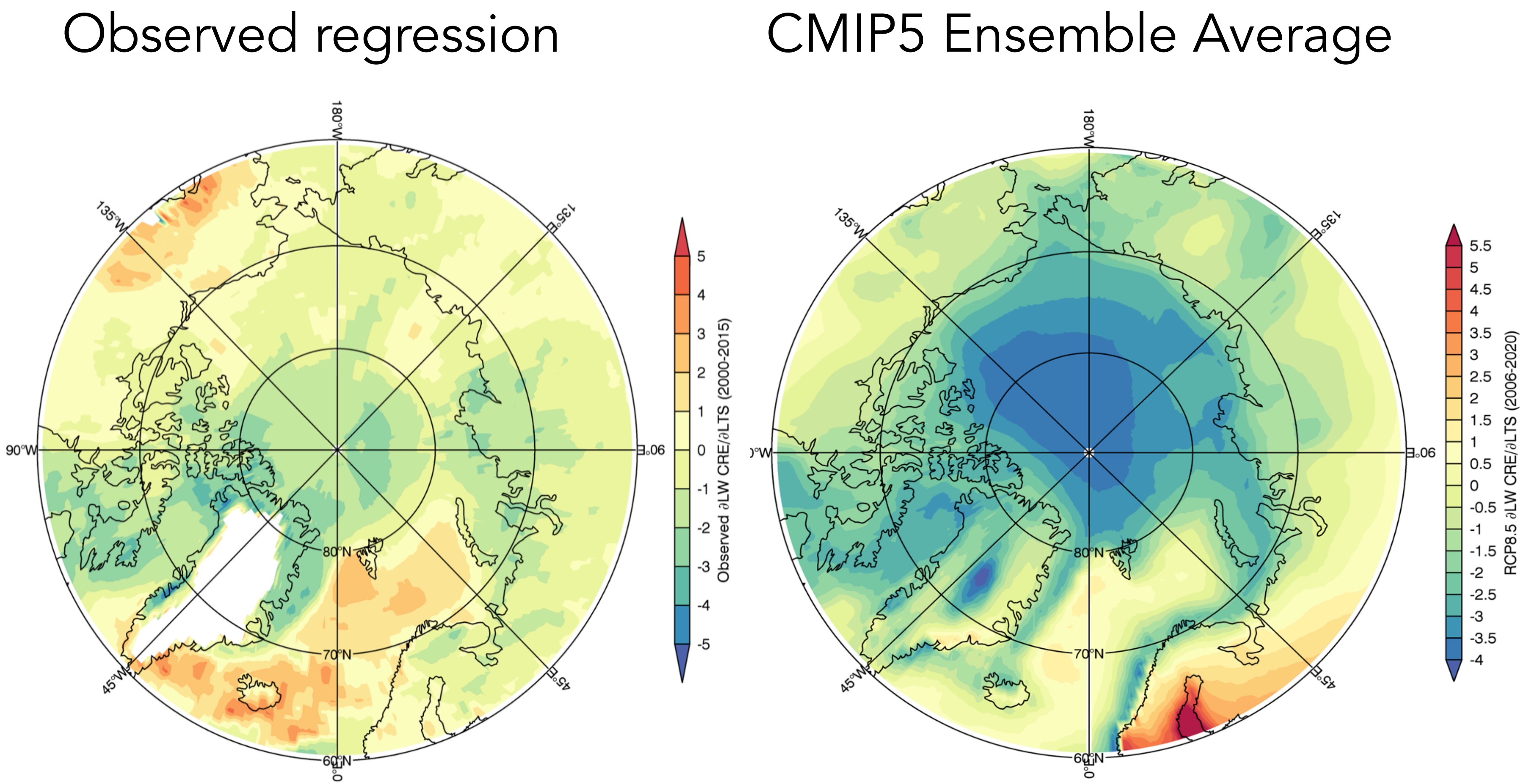
Ensemble Average transient change in LTS

RCP8.5: Ensemble Average projected LW CRE change 2080s minus present-day



Largest changes in LWCRE are found in the central Arctic.

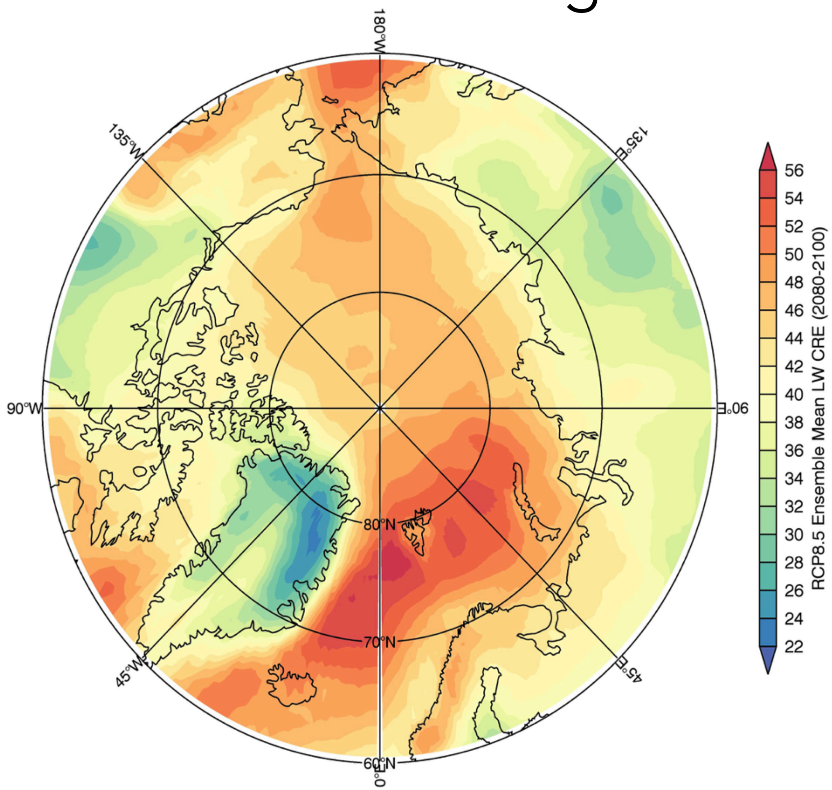
Inter-annual variability of LTS and LW CRE



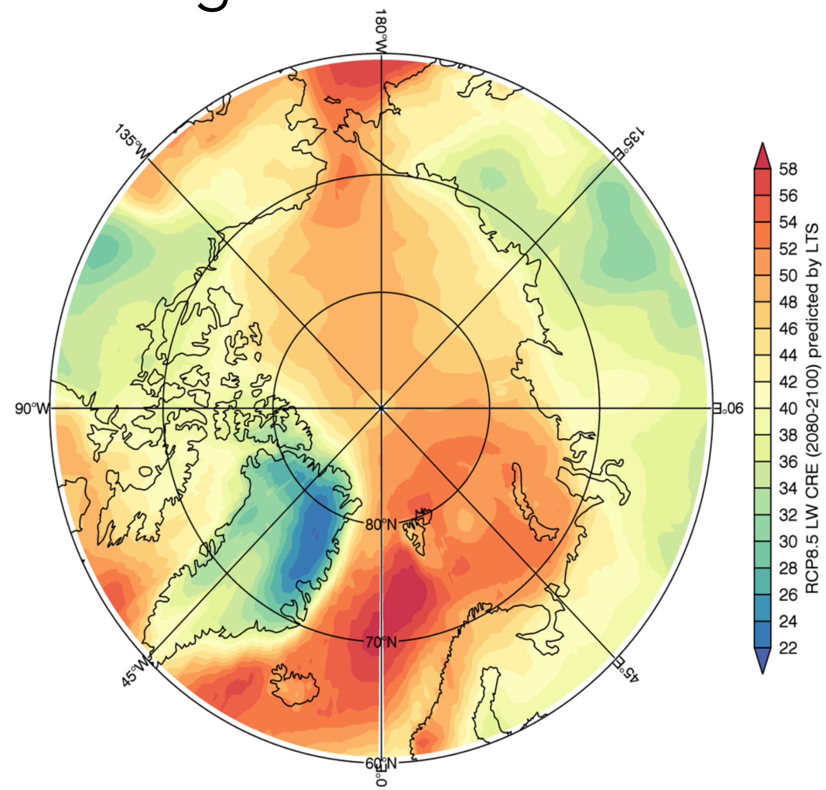
LW CRE-LTS regression slopes in climate models are more than 2 times larger than observations show over portions of the Arctic.

Can this regression be used to predict LW CRE change in 2080?

Ensemble average:

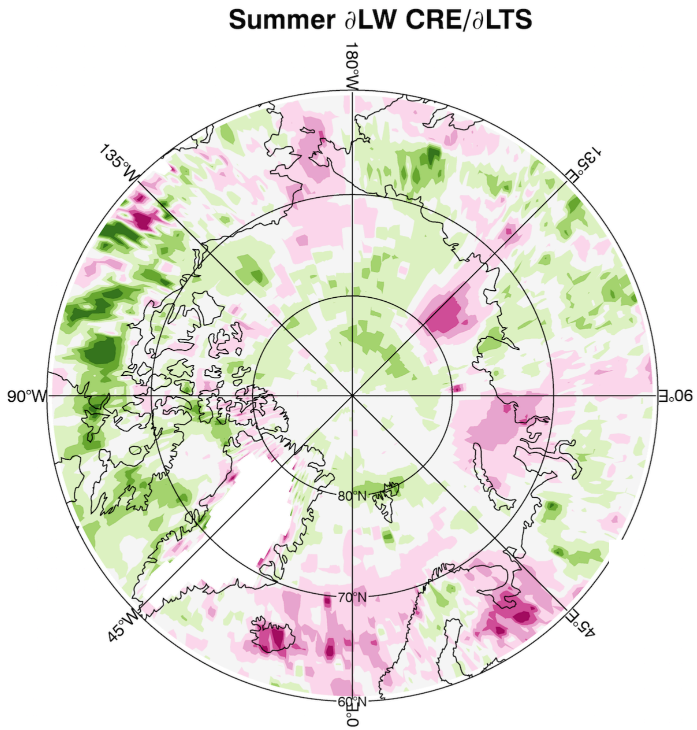


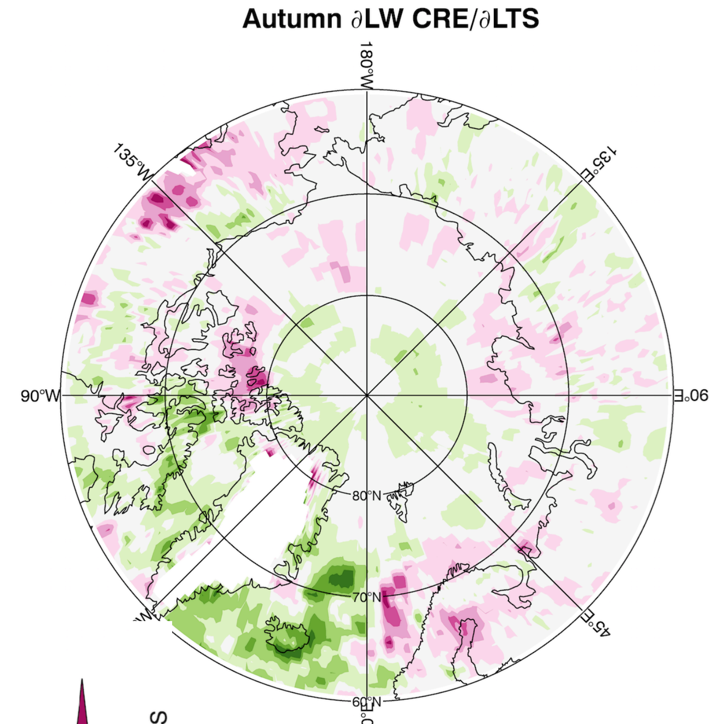
Regression result:

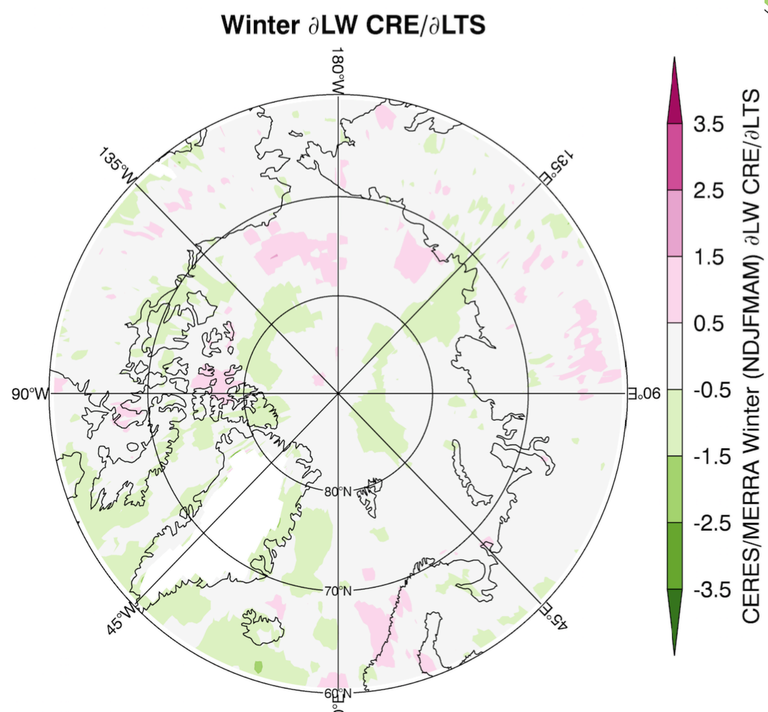


The patterns from the ensemble average and regression result agree well and the regression residuals are ~10-40%.

Inter-annual variability of LTS and LW CRE: CERES+MERRA2

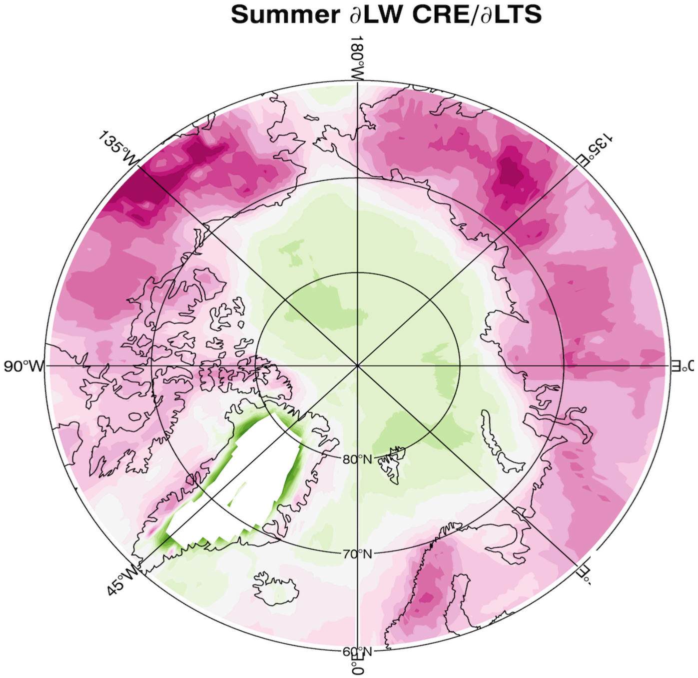


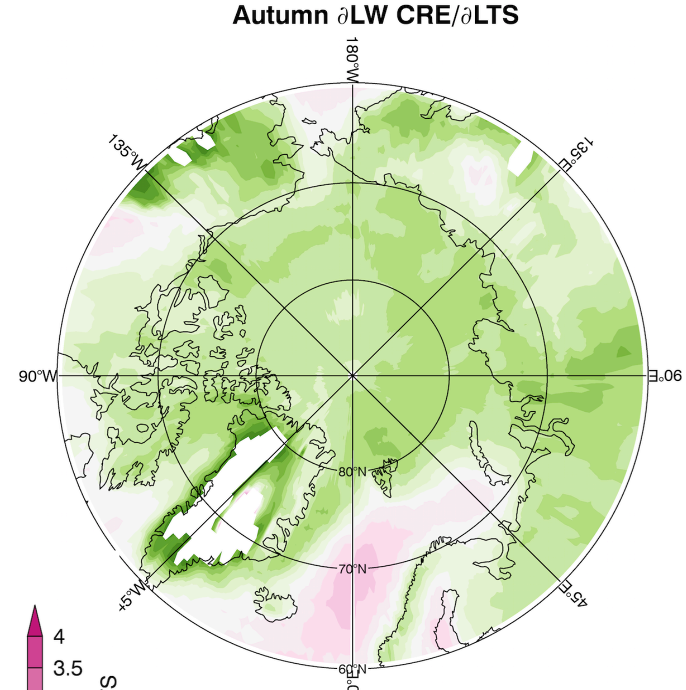


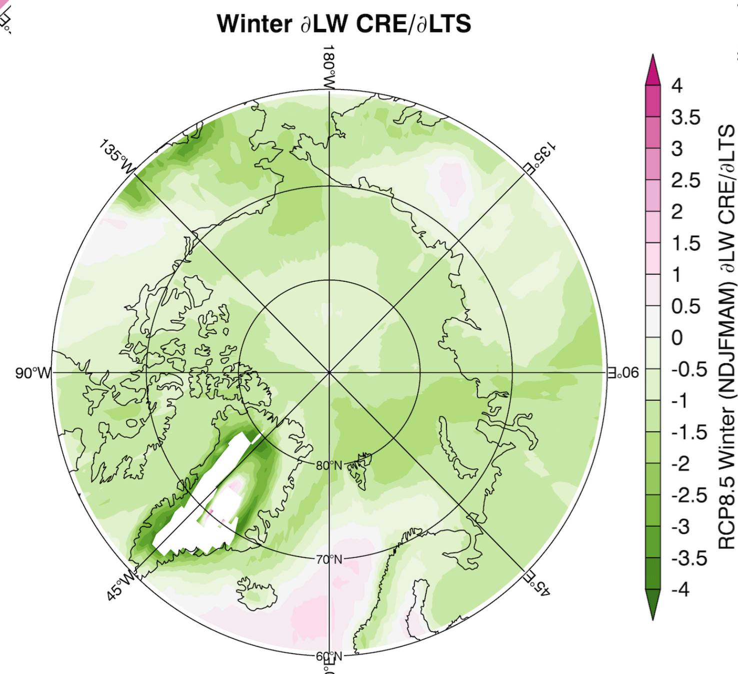


LW CRE-LTS seasonal regression slopes are noisy.

Inter-annual variability of LTS and LW CRE: CMIP5 RCP8.5







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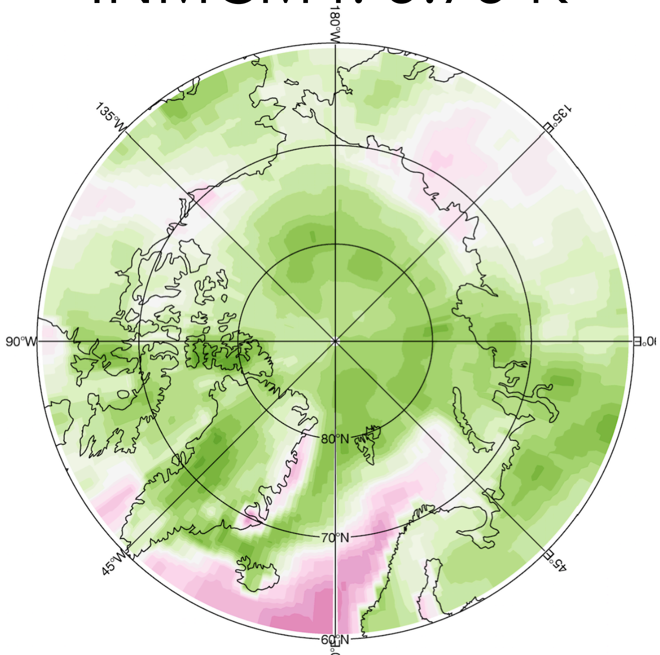
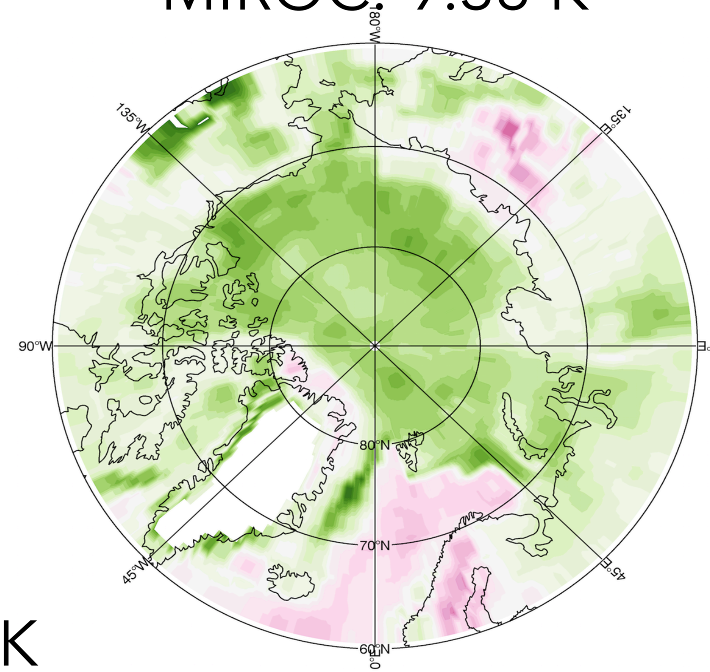
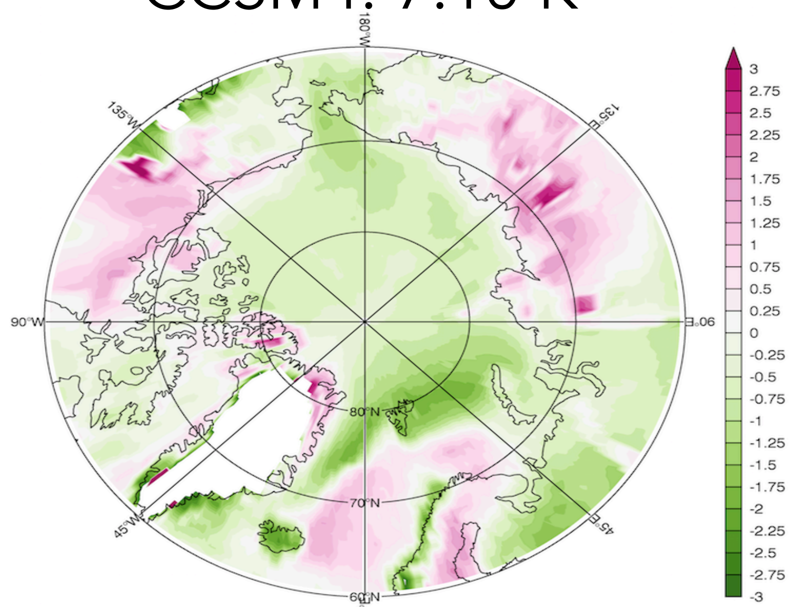
INMCM4: 5.75 K



MIROC: 9.38 K



CCSM4: 7.10 K



Model-to-model variations are largest over the Central Arctic and in the Barents Sea MIZ

Takeaway messages:

- Lower tropospheric stability, an excellent diagnostic for Arctic low cloud properties and surface radiative effects.
- Small change in atmospheric states can equal a large cloud feedback! A small change in the frequency of occurrence of atmosphere states can yield a larger Arctic cloud feedback than any cloud response to sea ice.
- Too strong LW CRE response to a reductions in Arctic stability. Over the central Arctic, the LW CRE sensitivity to a change in LTS in climate models is much stronger (more than 2 times in places) than observations show.
- Potentially significant amplifying sea ice-cloud feedback in fall. Our results indicate that the cloud response to sea ice reduction in fall could delay the fall freeze-up and influence the variability in sea ice extent and volume, under certain meteorological conditions; It only takes 1 Wm^{-2} to make a big difference.

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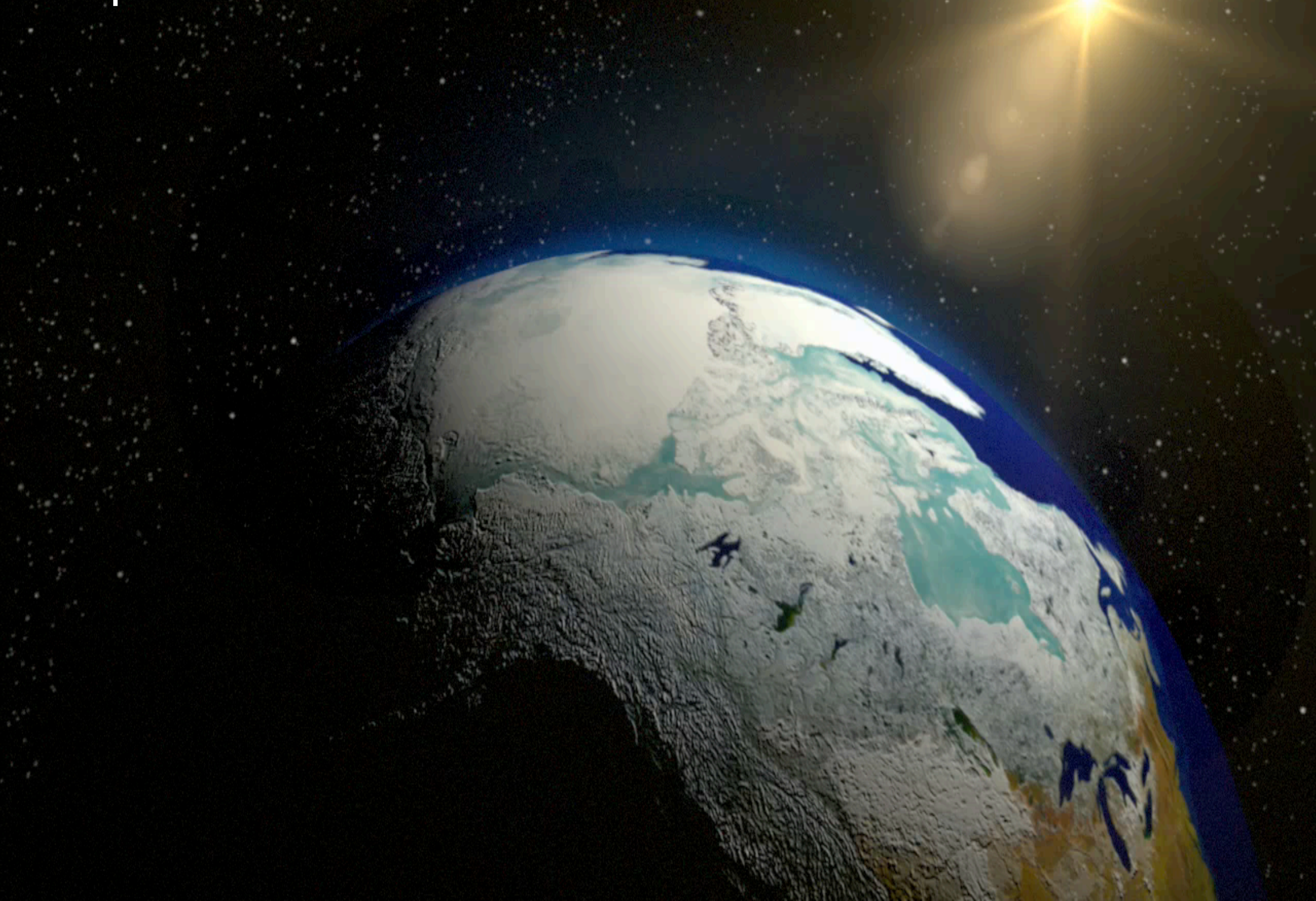
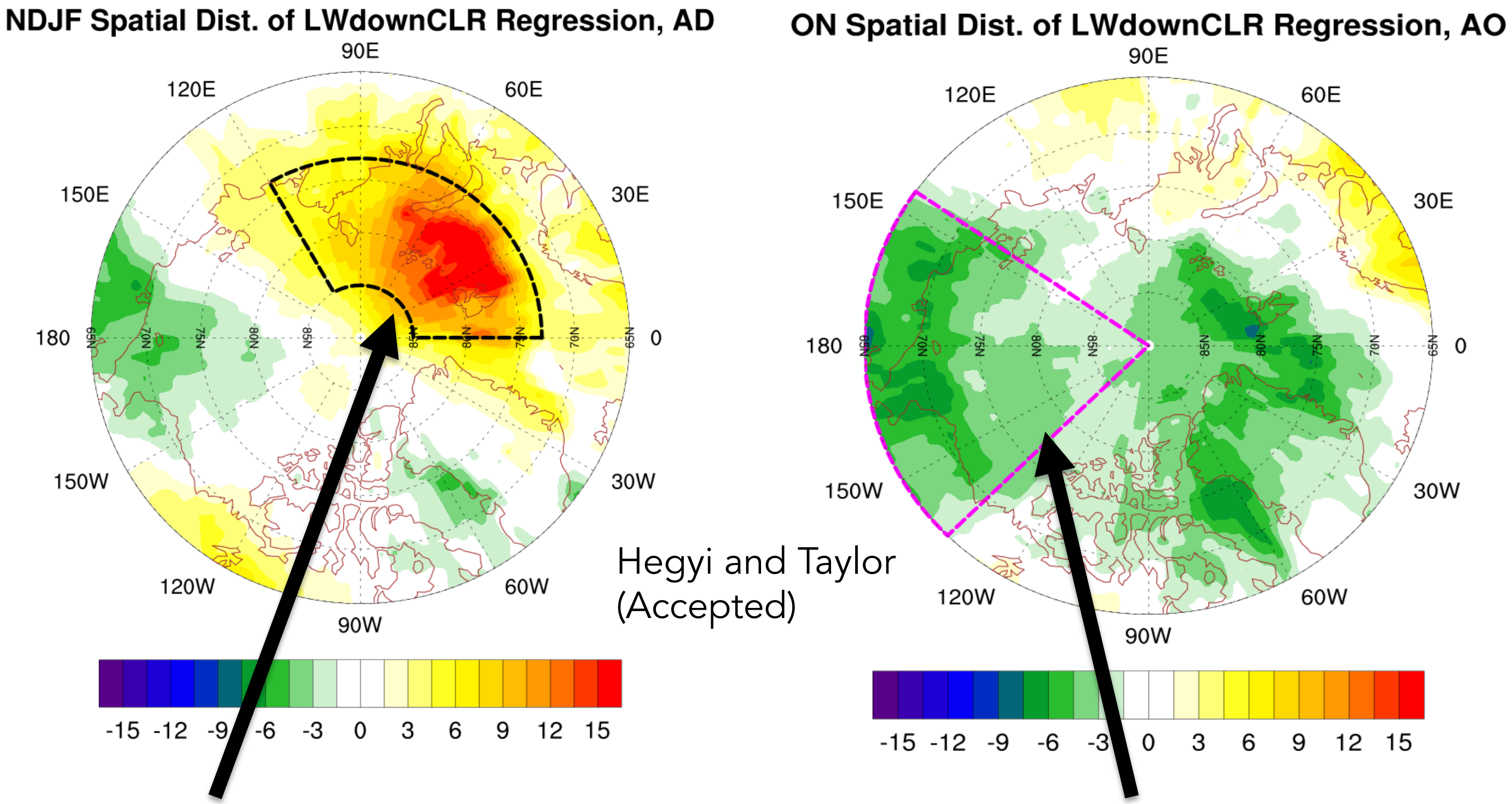
Importance of Arctic Clouds



Any way the wind blows: Circulation and the Arctic Surface Energy Budget



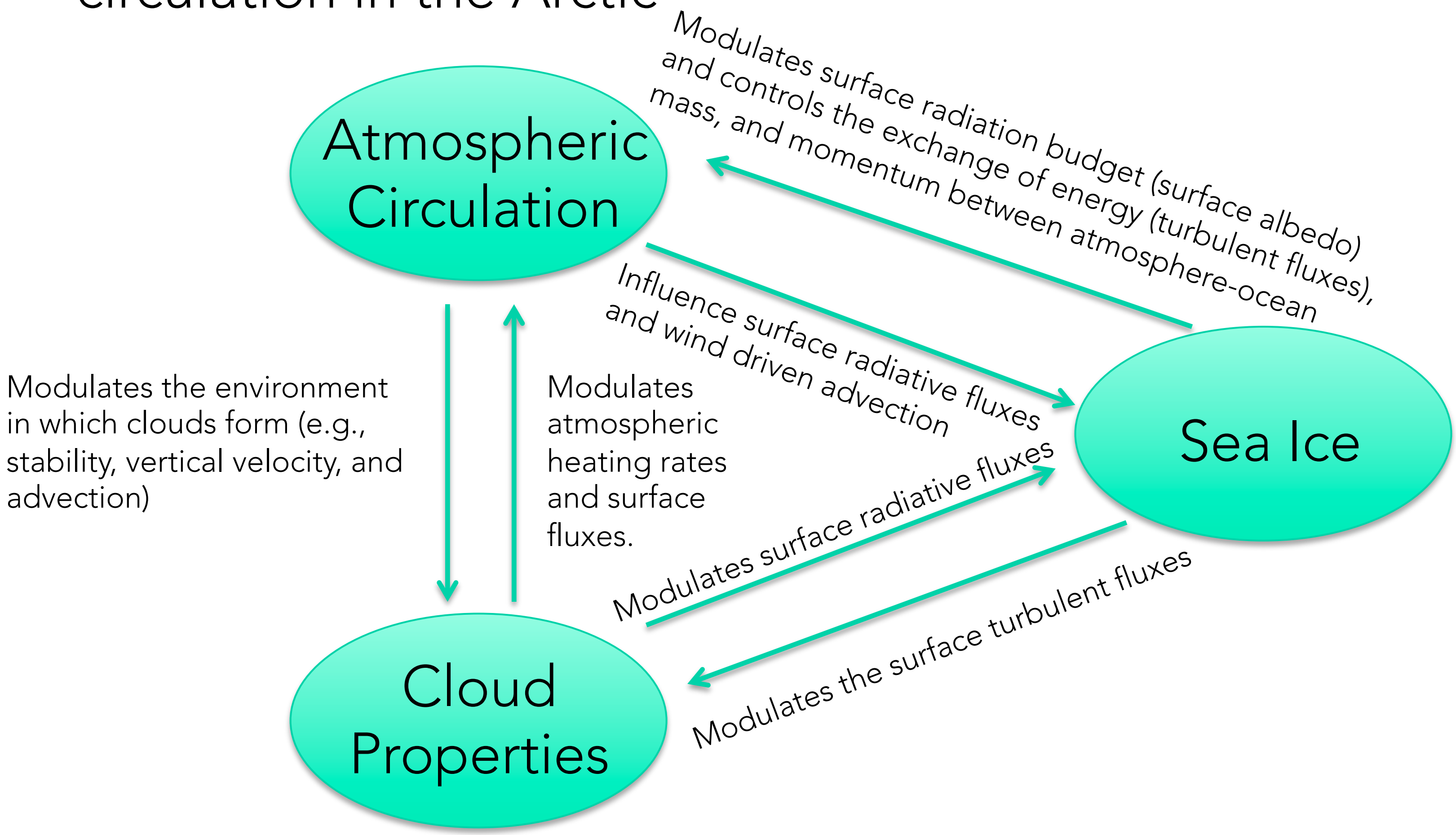
Hegyi and Taylor (Accepted)

Positive AD: Significant positive clear-sky downwelling LW anomaly.

Positive AO: Significant negative clear-sky downwelling LW anomaly.

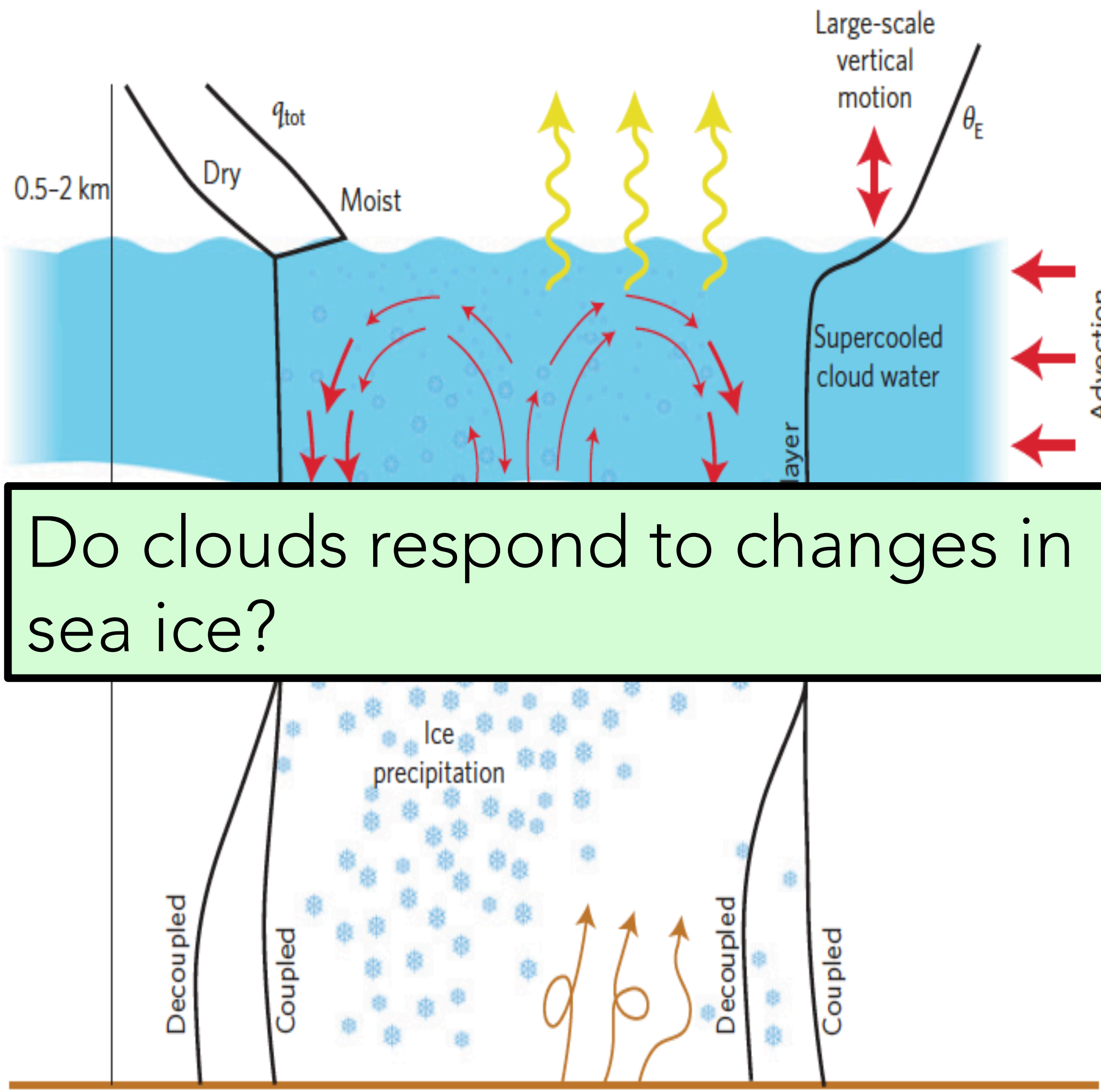
How do we reach the finish line?

Understanding the coupling between the cloud and circulation in the Arctic



In the Arctic, we cannot consider the interactions between clouds and the circulation without considering the sea ice state because sea ice influences both clouds and circulations.

Arctic Low Cloud Processes



Do clouds respond to changes in sea ice?

Radiative Cooling
- Drives buoyant production of turbulence
- Forces direct condensation within inversion layer
- Requires minimum amount of cloud liquid water

Microphysics
- Liquid forms in updrafts and sometimes within the inversion layer
- Ice nucleates in cloud
- Rapid ice growth promotes sedimentation from cloud

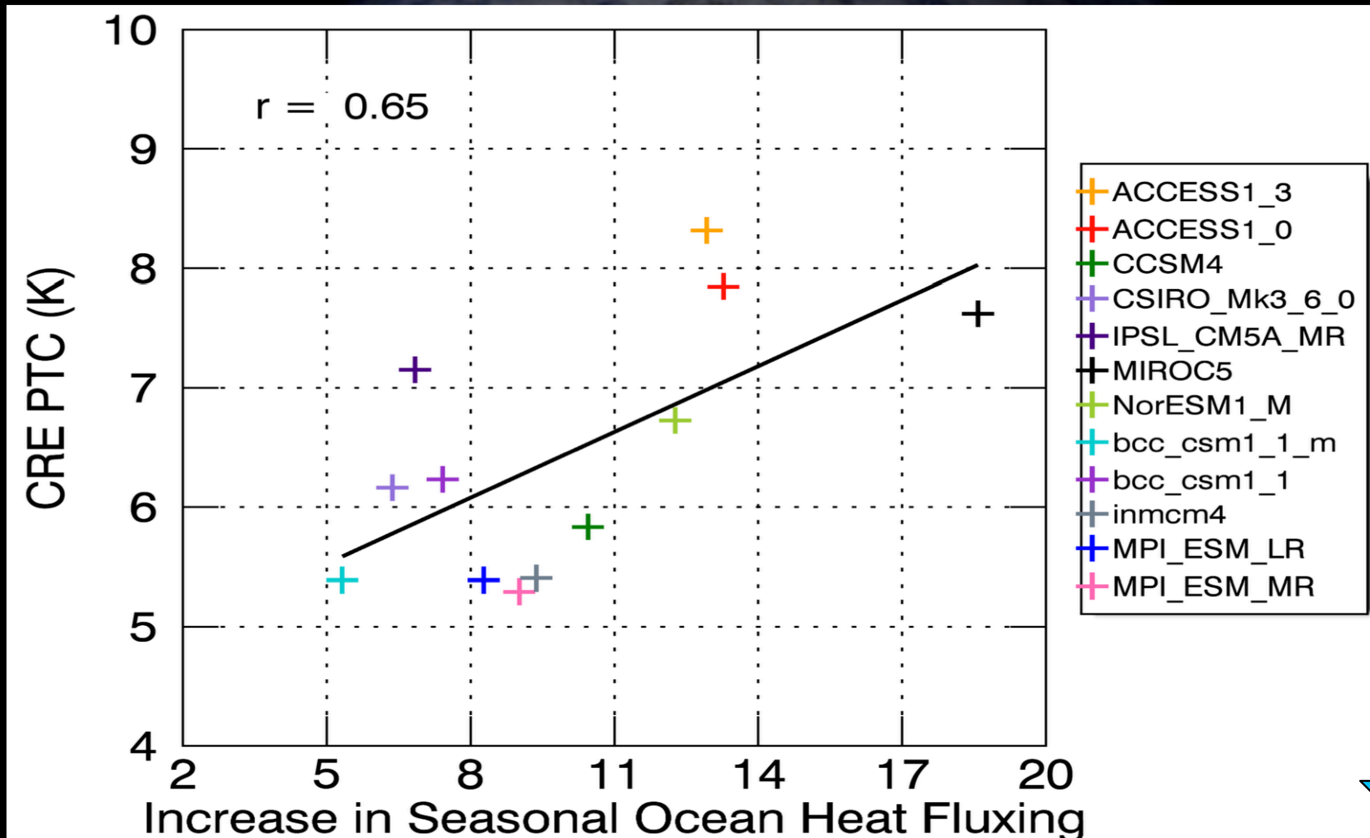
Dynamics
- Cloud-forced turbulent mixed layer with strong narrow downdrafts, weak broad updrafts, and q_{tot} and θ_E nearly constant with height
- Small-scale, weak turbulence in cloudy inversion layer
- Large-scale advection of water vapour important

Surface Layer
- Turbulence and q contributions can be weak or strong
- Sink of atmospheric moisture due to ice precipitation
- Surface type (ocean, ice, land) influences interaction with cloud

The influence of the surface type on the cloud properties implies an interaction between clouds and sea ice that may significantly influence Arctic climate change.

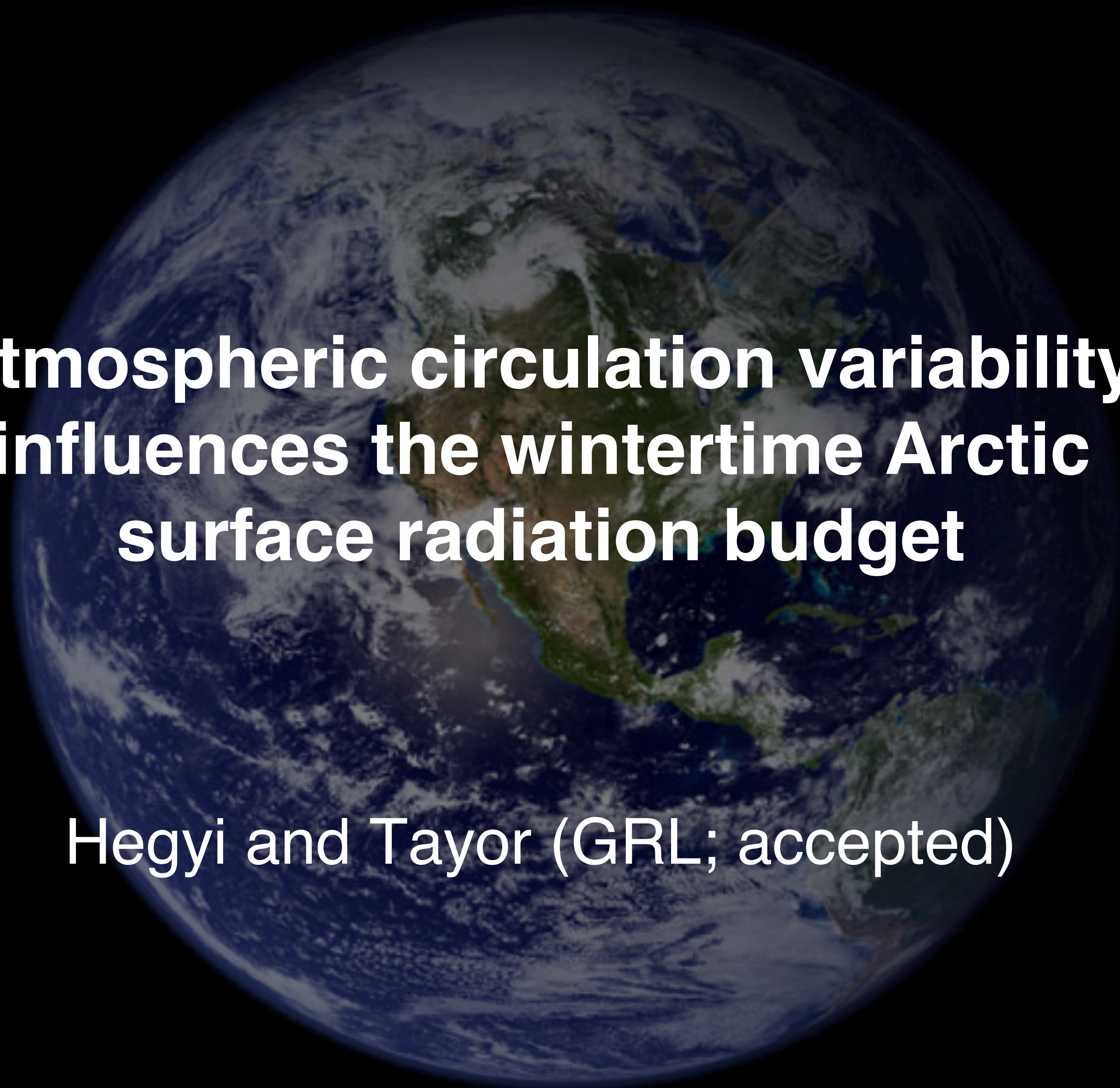
Morrison et al. (2012; Nature Geoscience)

Larger CRE results in more summer storage



Increases in storage facilitates cloud formation and IR feedbacks

Increases in clouds strengthen the CRE PTC

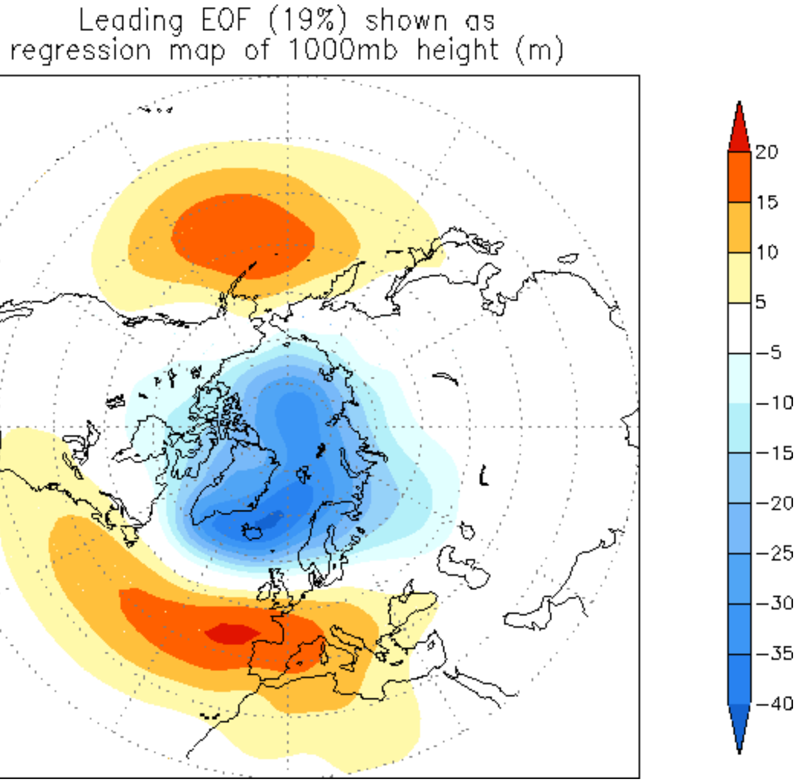


Atmospheric circulation variability influences the wintertime Arctic surface radiation budget

Hegyi and Tayor (GRL; accepted)

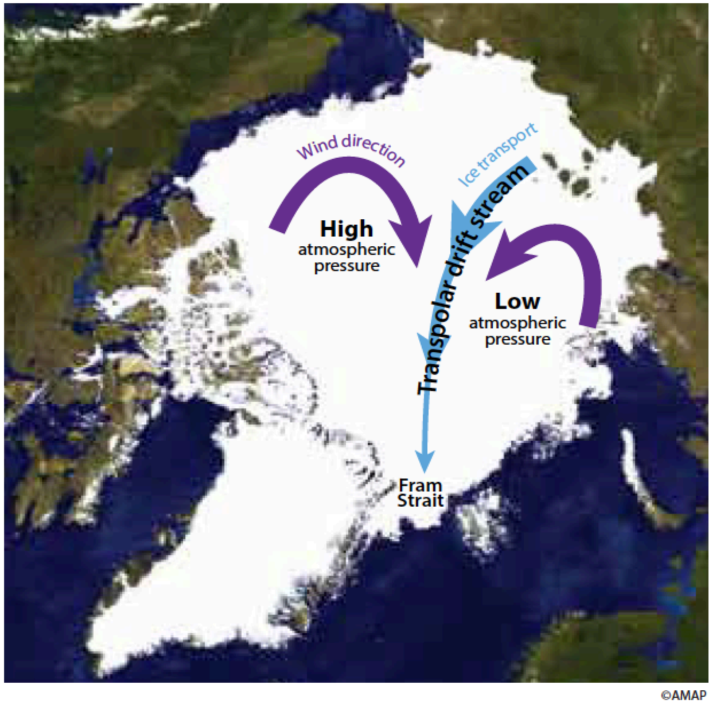
Defining the Arctic circulation

AO: Leading EOF of the 1000 hPa height pattern from 20-90N.



Zonally symmetric

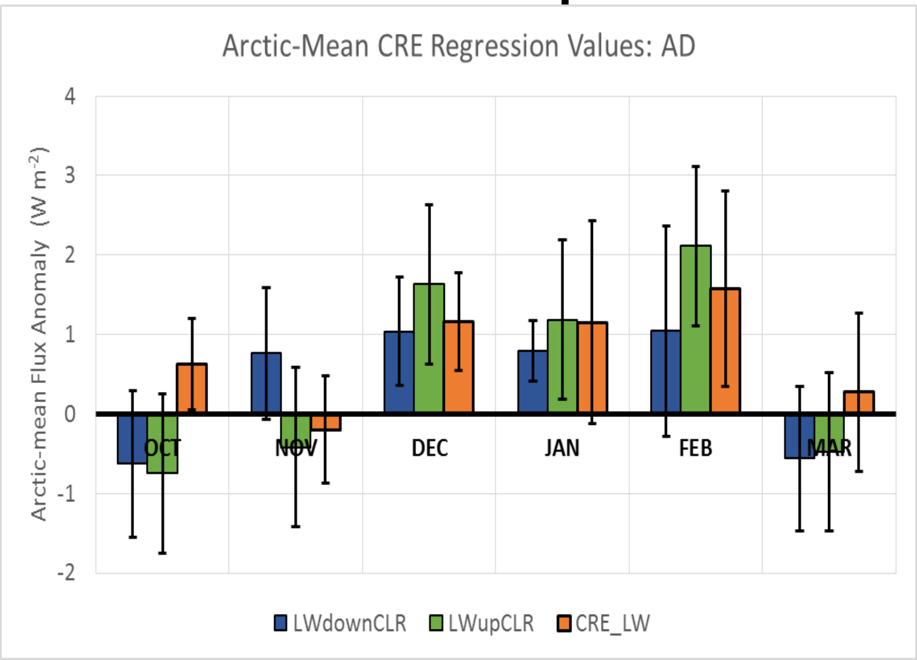
AD: Leading EOF of the 1000 hPa height pattern from 70-90N.



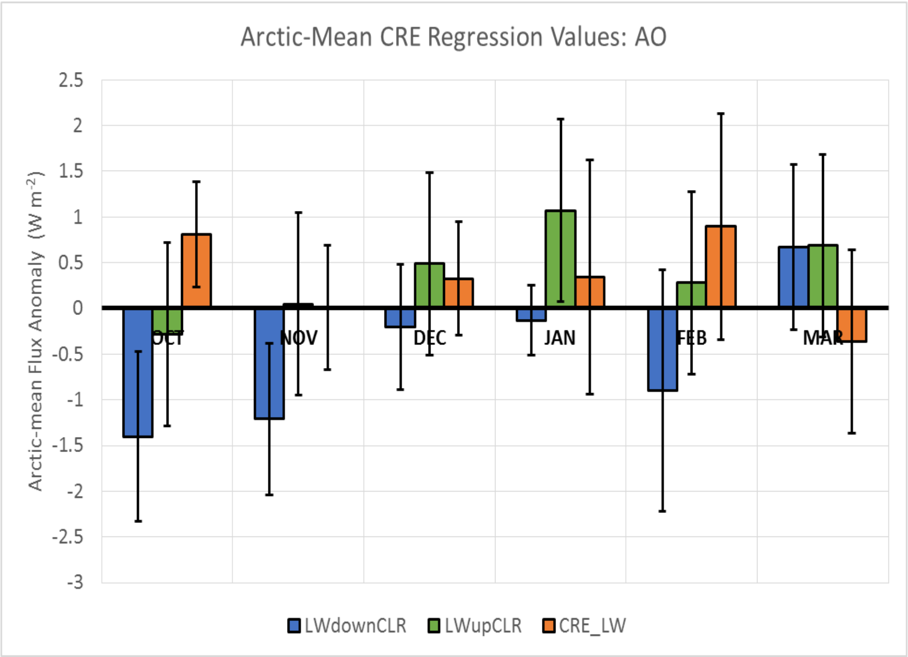
Zonally asymmetric

Any way the wind blows: Circulation and the Arctic Surface Energy Budget

Arctic Dipole

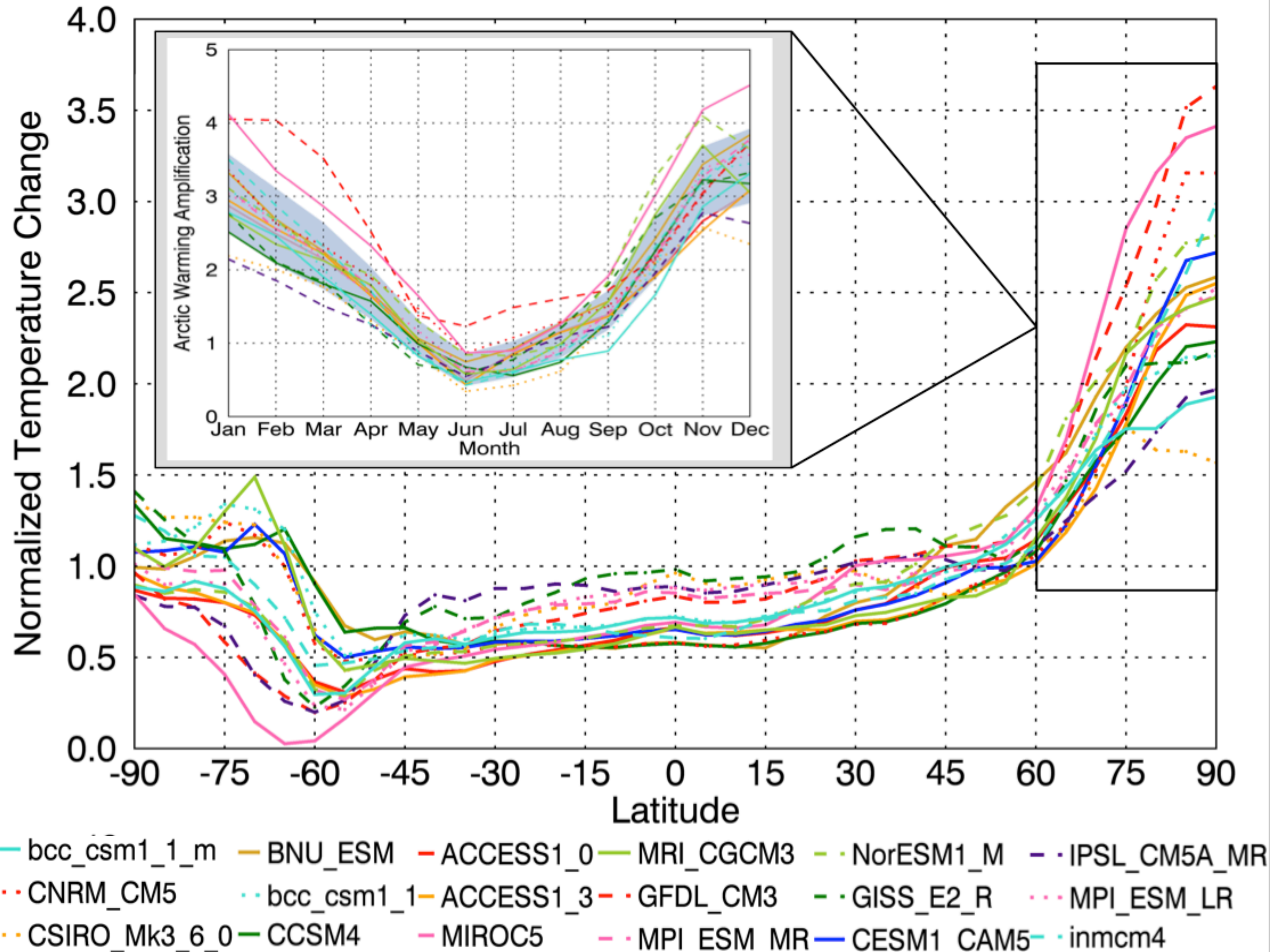


Arctic Oscillation



Robust, domain averaged associations between the Arctic circulation and the surface radiation budget.

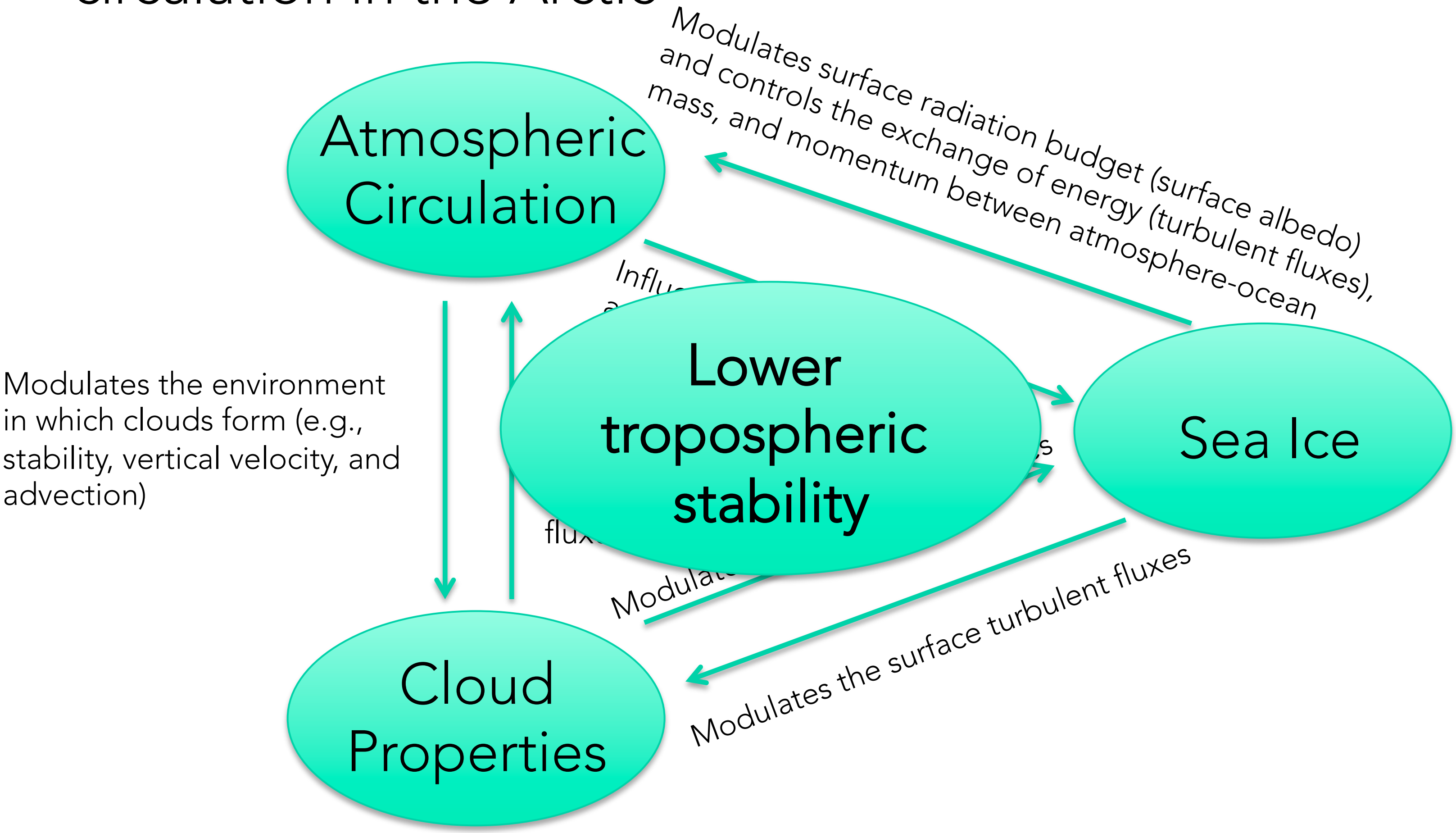
Hegyi and Taylor (GRL; accepted)



Normalized Temperature Change
Latitude
Arctic Warming Amplification
Month
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
bcc_csm1_1_m
BNU_ESM
ACCESS1_0
MRI_CGCM3
NorESM1_M
IPSL_CM5A_MR
CNRM_CM5
bcc_csm1_1
ACCESS1_3
GFDL_CM3
GISS_E2_R
MPI_ESM_LR
CSIRO_Mk3_6_0
CCSM4
MIROC5
MPI_ESM_MR
CESM1_CAM5
inmcm4

Another 3-legged stool?

Understanding the coupling between the cloud and circulation in the Arctic



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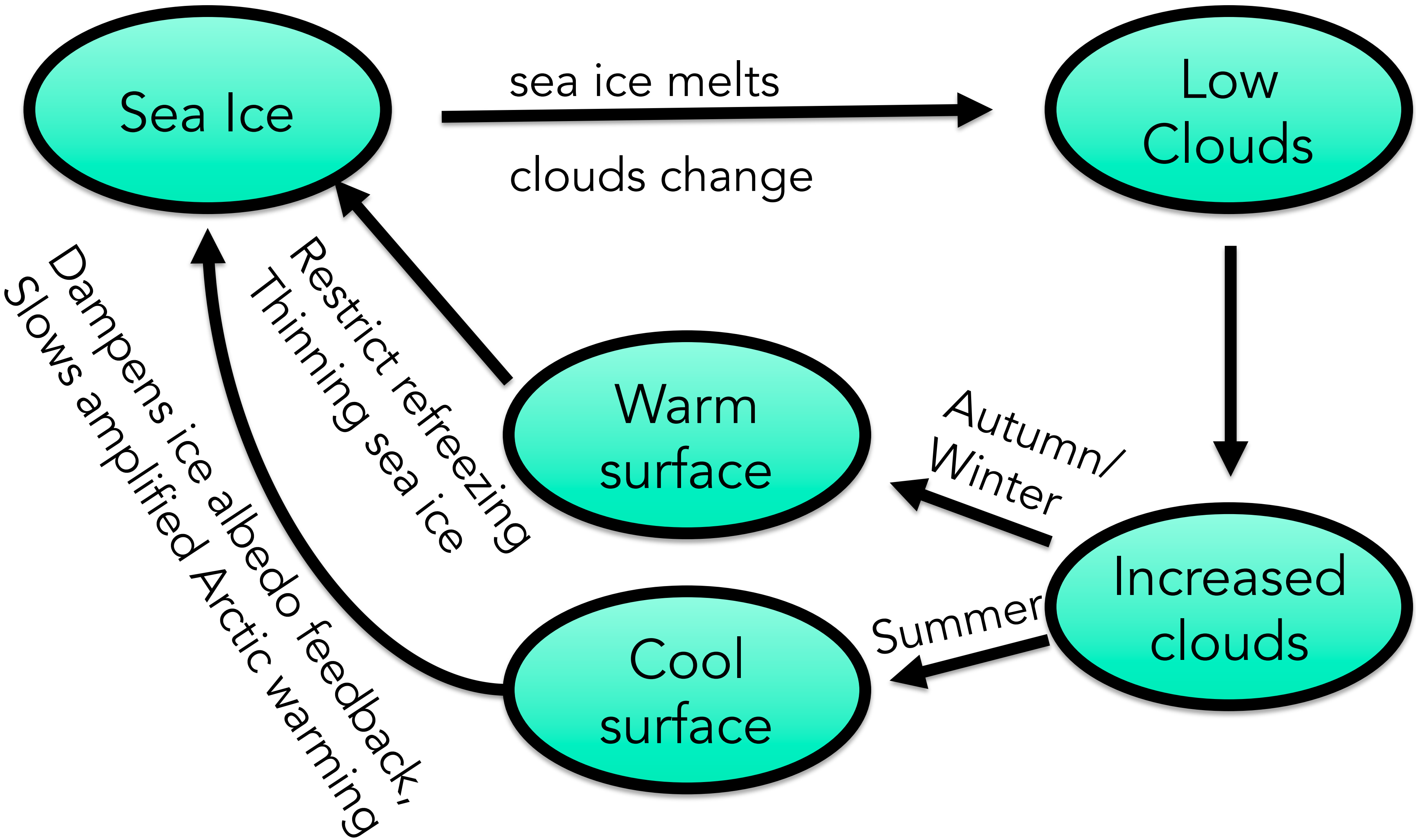
Example pathways: Sea Ice-Clouds



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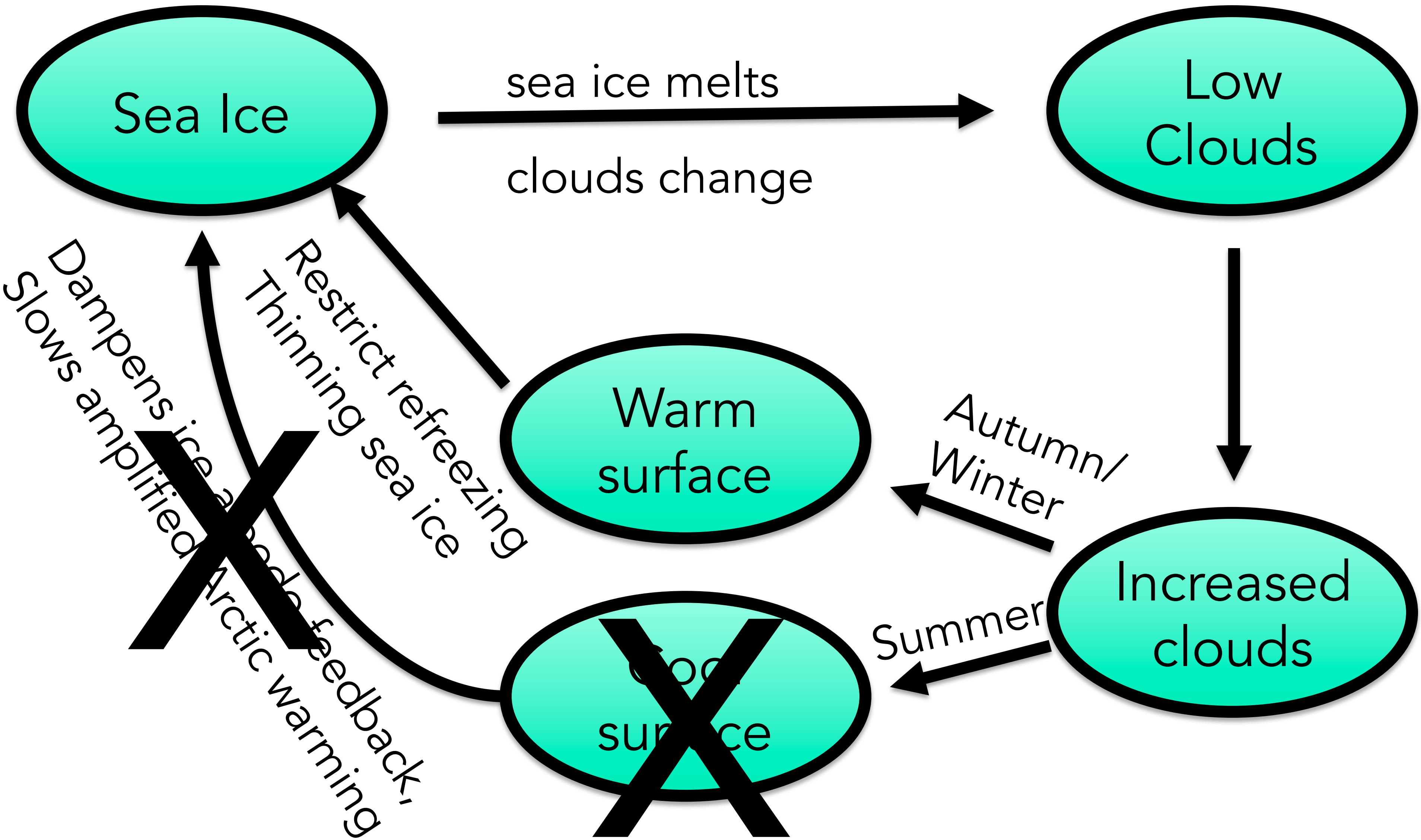
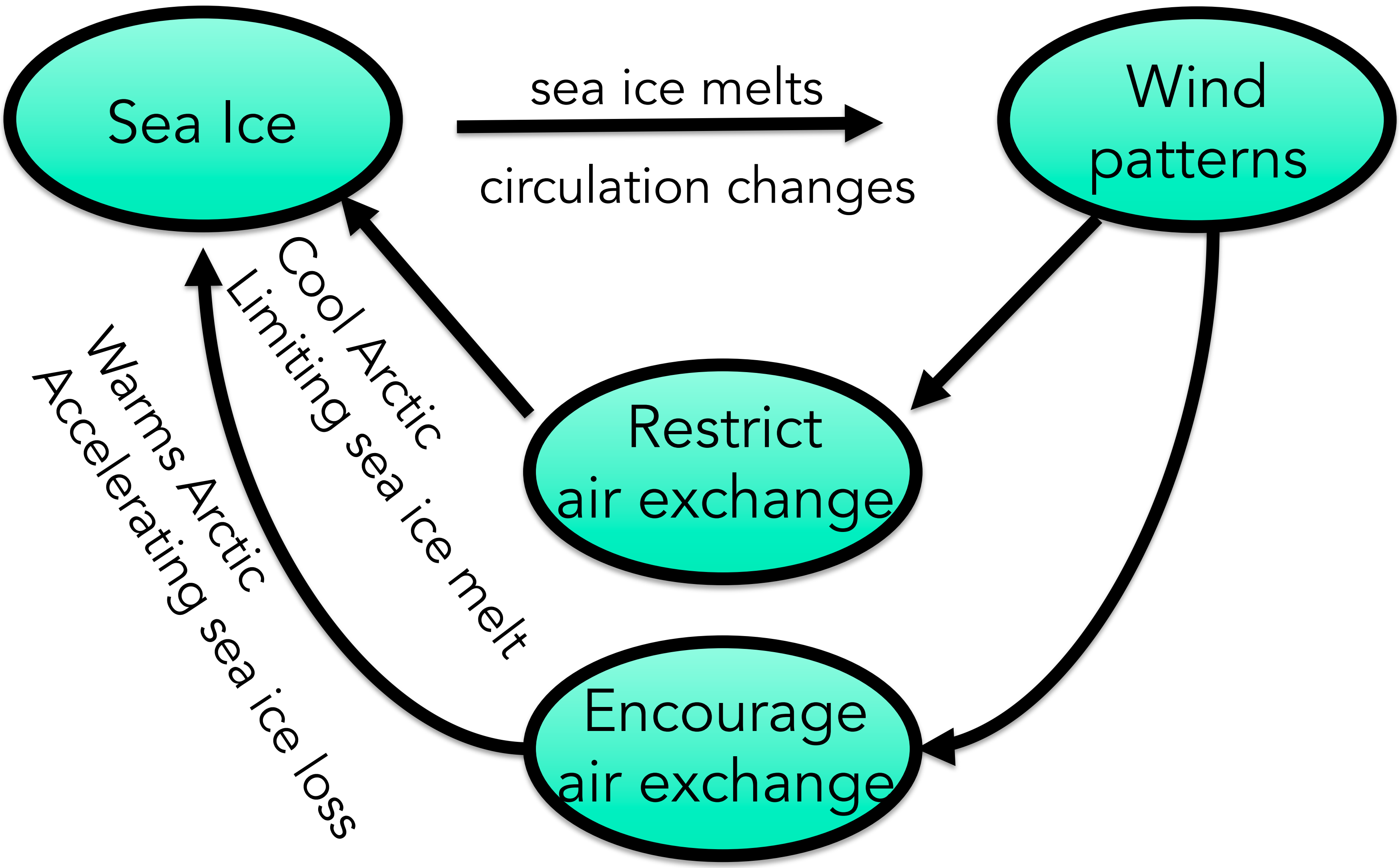
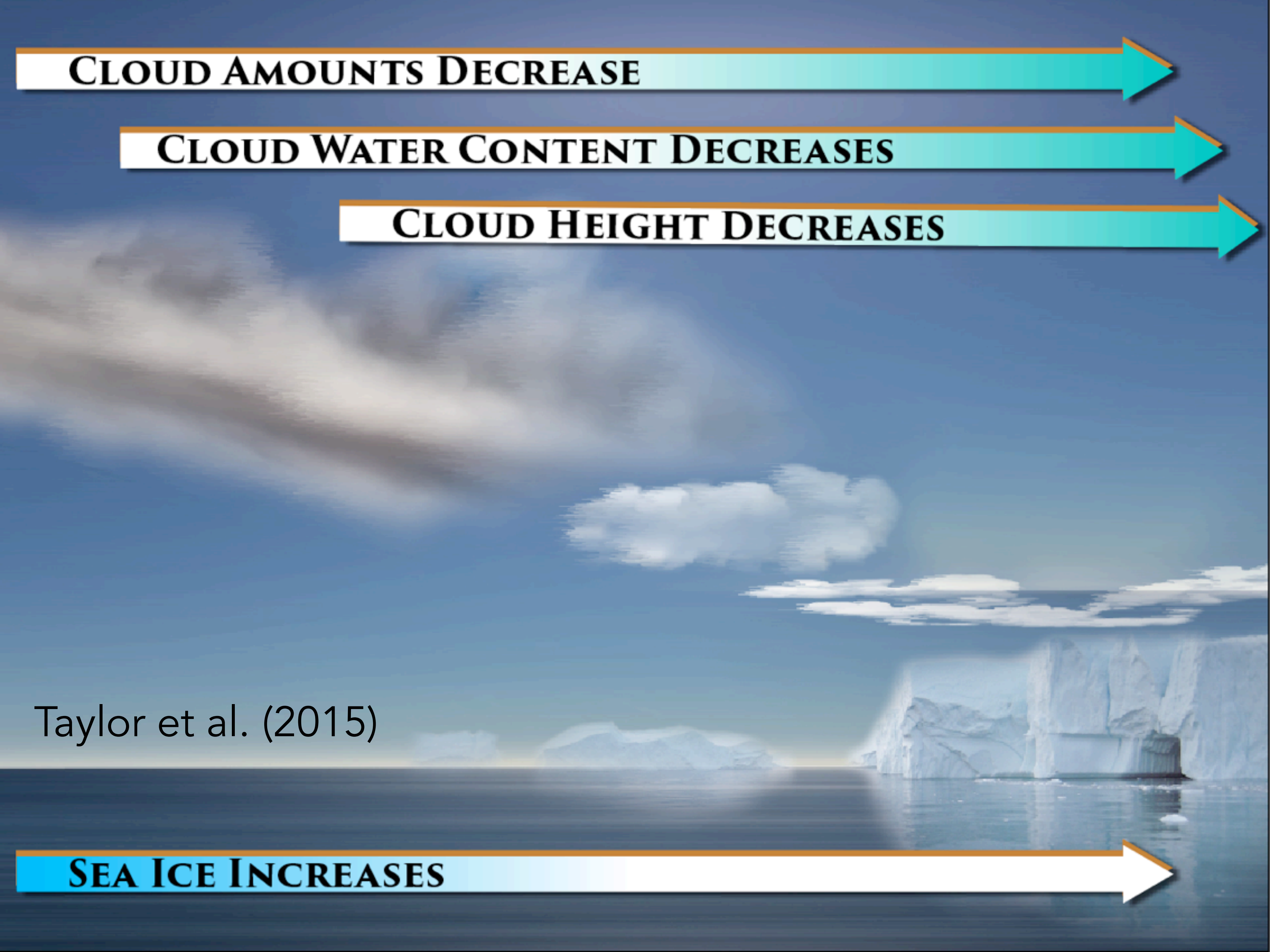
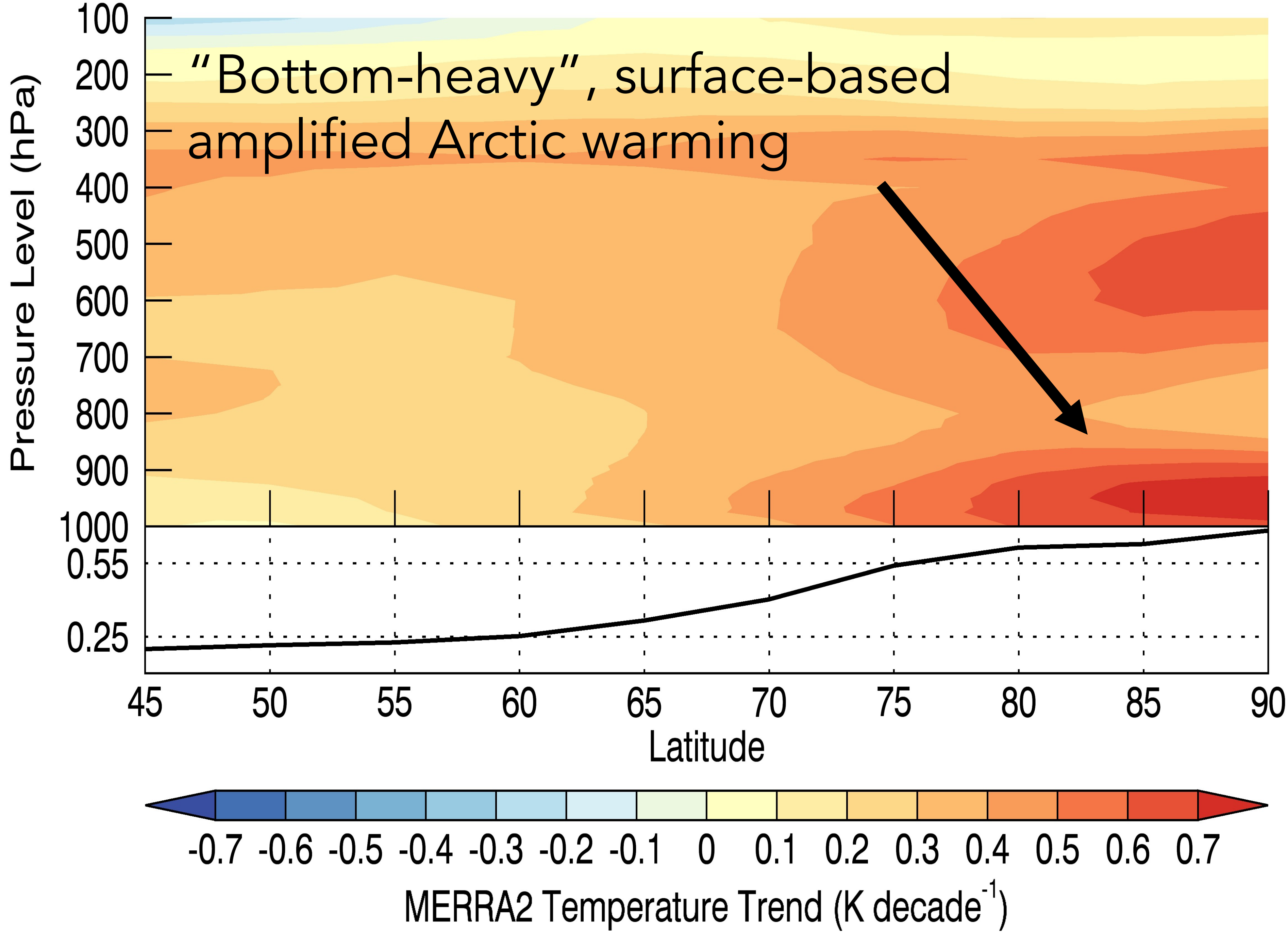


Example pathways: Sea Ice-Circulation



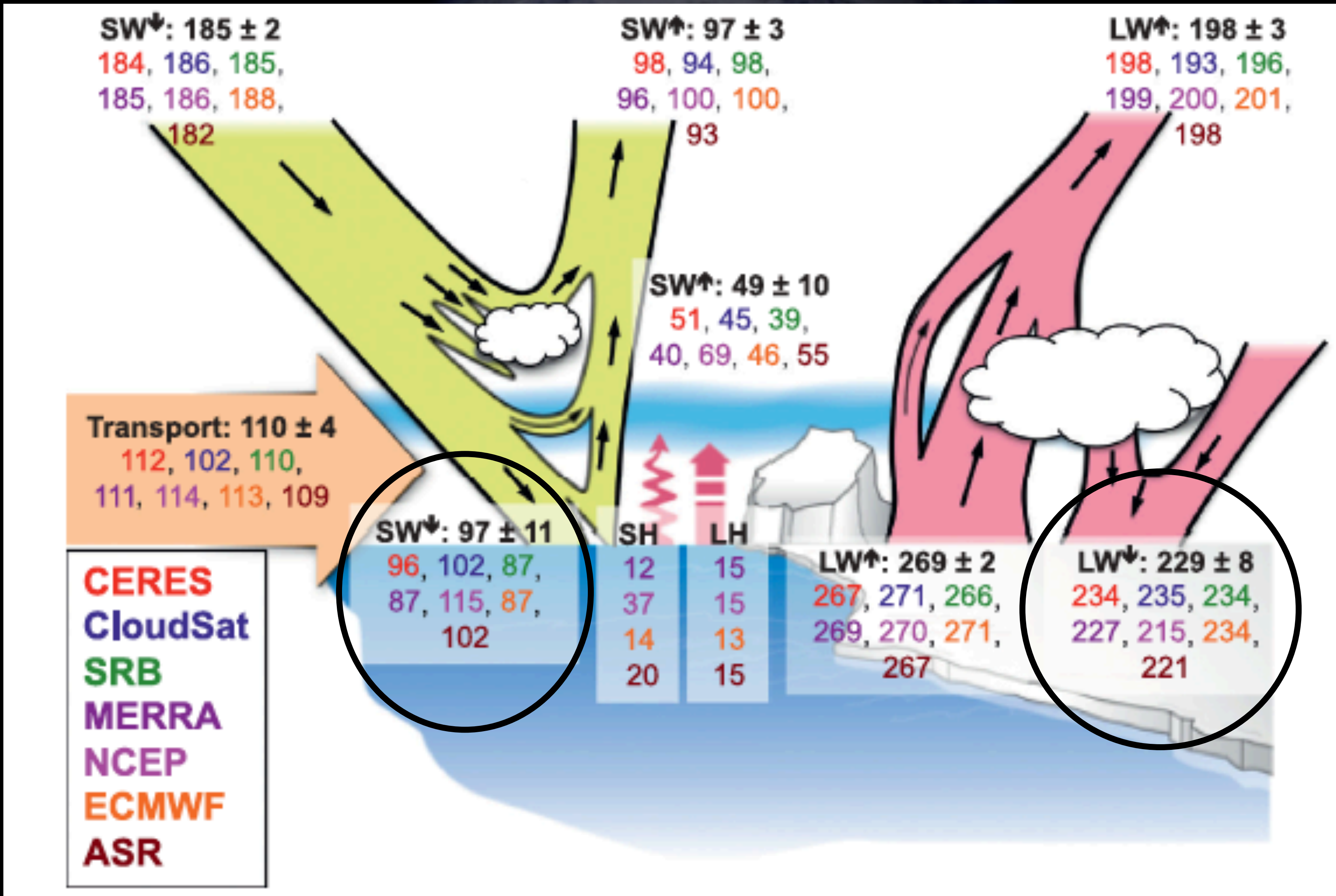


Taylor et al. (2015)

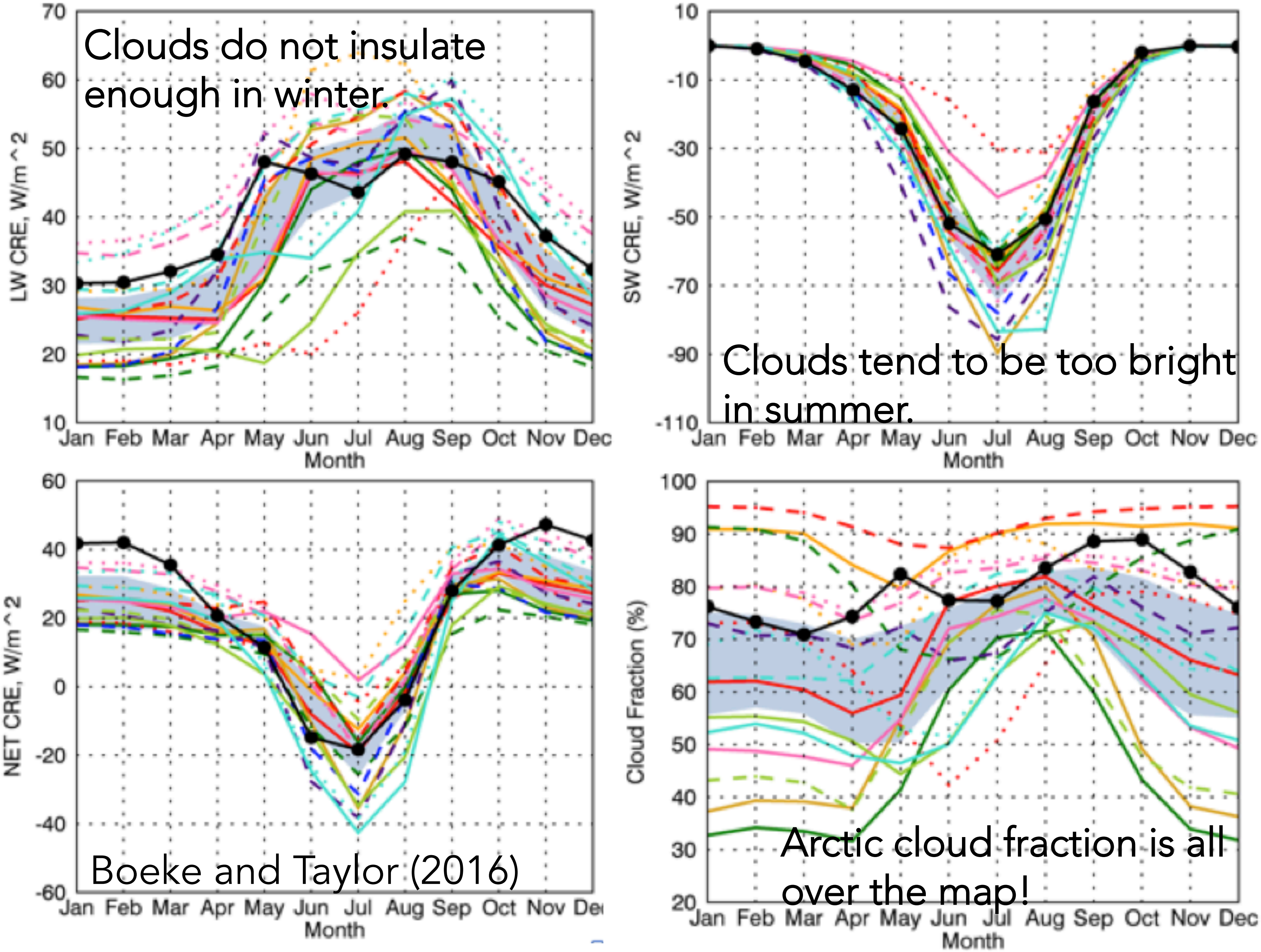

"Bottom-heavy", surface-based
amplified Arctic warming
Pressure Level (hPa)
100
200
300
400
500
600
700
800
900
1000
0.55
0.25
45
50
55
60
65
70
75
80
85
90
Latitude
-0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
MERRA2 Temperature Trend (K decade^{-1})

Arctic surface energy budget: Current Status

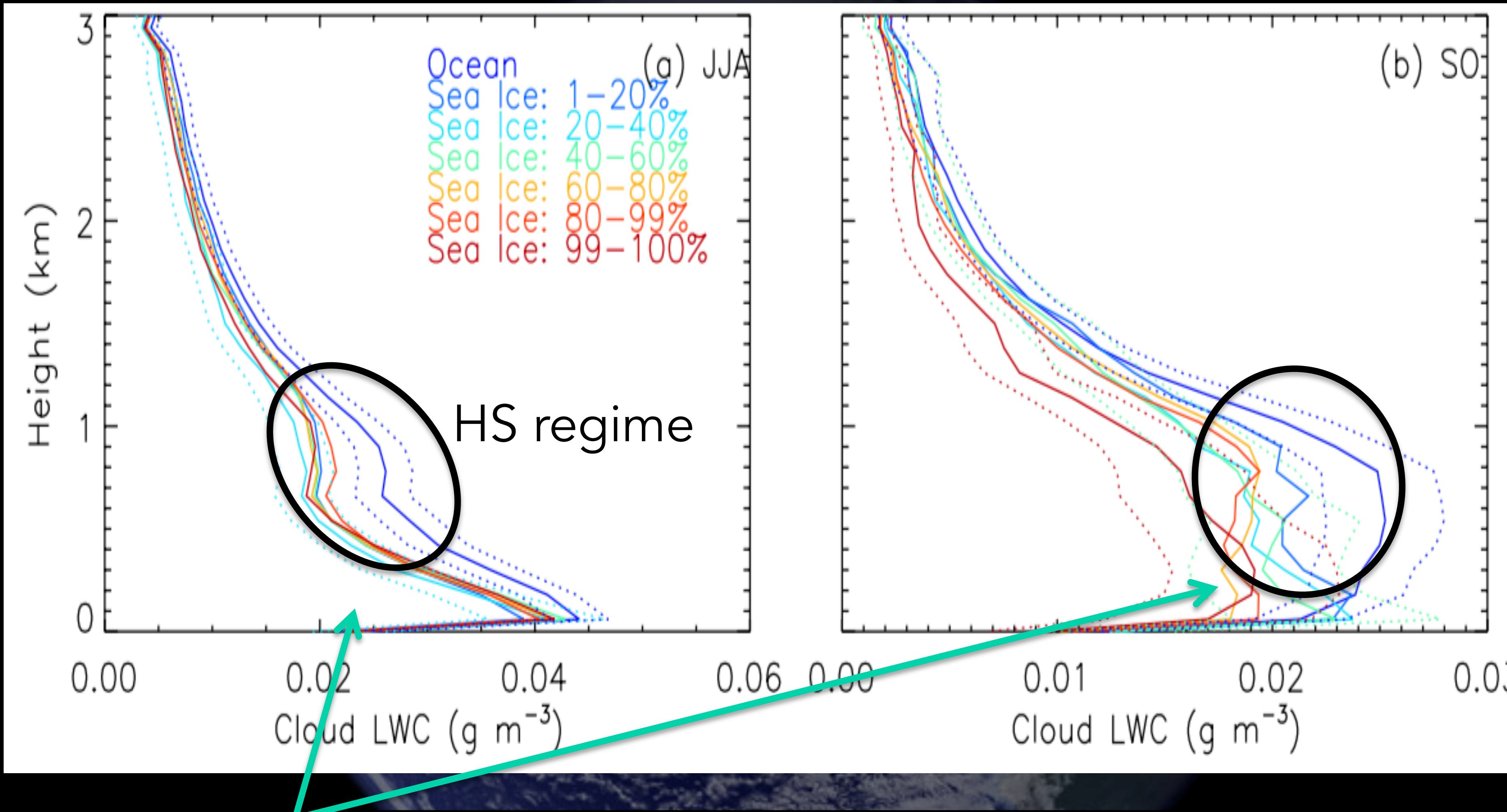
Christensen et al. (2016; BAMS)



CMIP5 vs. CERES Surface Cloud Radiative Effects

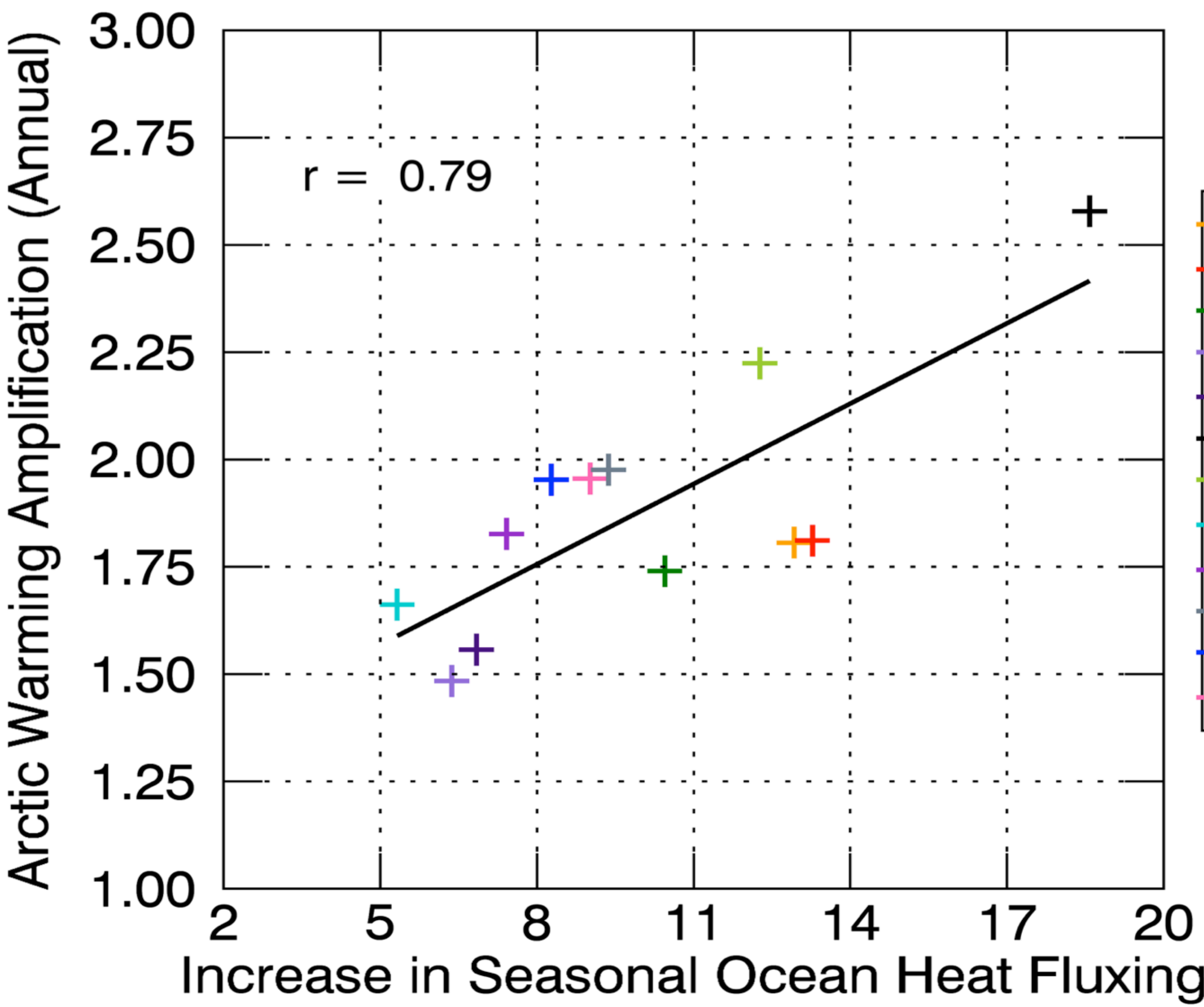


LWC Vertical Profile vs. Sea ice



- General decrease in LWC is found with increased sea ice concentration in both summer and autumn.
- Statistically significant differences the LWC between 500 m and 1.2 km are found in summer and autumn at 0% and 20-40% sea ice concentration.

A big role for the ocean!



Boeke and Taylor (in prep.)

Relationship between LTS-CRE by atmospheric regime

Units: W m^{-2}

Atmospheric Regime	Summer (JJA)		Fall (SO)		Winter (NDJFMAM)	
	LW CRE	SW CRE	LW CRE	SW CRE	LW CRE	SW CRE
VHS (LTS >24 K)	40.6	-57.5	37.9	-10.8	24.4	-8.1
HS (16<LTS<24 K)	50.1	-70.1	53.0	-16.6	37.9	-11.8
S (LTS<16 K)	55.7	-80.8	59.5	-20.2	53.6	-19.7
UL (ω_{500} < -8.6 hPa day^{-1})	51.8	-85.1	56.6	-22.3	48.6	-18.6

Taylor (2017)